HOT DRY ROCK ENERGY

Progress Report

Fiscal Year 1993

by

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EXECUTIVE SUMMARY

Overview: Extended flow testing at the Fenton Hill Hot Dry Rock (HDR) test facility concluded in Fiscal Year 1993 with the completion of Phase 2 of the long-term flow test (LTFT) program. As is reported in detail in this report, the second phase of the LTFT, although only 55 days in duration, confirmed in every way the encouraging test results of the 112-day Phase 1 LTFT carried out in Fiscal Year 1992.

Interim flow testing was conducted early in FY 1993 during the period between the two LTFT segments. In addition, two brief tests involving operation of the reservoir on a cyclic schedule were run at the end of the Phase 2 LTFT. These interim and cyclic tests provided an opportunity to conduct evaluations and field demonstrations of several reservoir engineering concepts that can now be applied to significantly increase the productivity of HDR systems.

The Fenton Hill HDR test facility was shut down and brought into standby status during the last part of FY 1993. Unfortunately, the world's largest, deepest, and most productive HDR reservoir has gone essentially unused since that time.

The injection pump problems which led to the suspension of the LTFT in July 1992 were resolved this year. Early in the year, two different diesel driven, reciprocating pumps were used for interim flow testing while a suitable replacement pump capable of extended operation under the standard LTFT operating conditions was sought. A centrifugal pump rented from REDA of Bartlesville, OK, proved to be well-suited to the job. The REDA pump was an electrically powered, multistage unit assembled specifically for the Fenton Hill application. It arrived at the HDR site in late January 1993.

A number of modifications to the site electric supply system were required to bring the REDA pump on-line, but once these were completed it operated with 100% reliability until it was returned to REDA upon expiration of the lease in late May. Although the centrifugal REDA pump lacked the operational versatility of the reciprocating pumps used in earlier HDR testing, its low initial cost and high reliability would no doubt make it the pump of choice for injection under the well-defined, steady-state operating conditions that would probably be typical of a commercial HDR power plant.

The transfer of HDR technology was promoted in Fiscal Year 1993 through a series of organized conferences as well as in a large number of meetings and communications with individual companies. Near the end of the fiscal year, the USDOE published a Notice of Program Interest soliciting input on participation in a project involving the marketing of energy derived from HDR resources. By early 1994, it was apparent that there was significant private sector interest in the practical application of HDR technology.

Completion of Steady-State Flow Testing: The operating regimen followed in conducting the Phase 2 LTFT was the same as that employed during Phase 1, and the production temperatures (182-184°C or 360-365°F) and flow rates (90-100 gpm) were virtually identical. The only significant difference between the two test phases was the water loss rate. Water lost to the underground rock mass had declined continually over the span of the Phase 1 LTFT to reach a level of about 12% of the injected volume by the time the test was suspended. Because the system was kept pressurized during the interim between the two test phases, the downward trend in water permeation into the underground rock body continued so that by the end of Phase 2, water losses were running about 7%.

Tracer test results during Phase 2 of the LTFT, like those of Phase 1, indicated that the modal volume (the volume filled with mobile fluid) of the reservoir was continually increasing, and that the circulating fluid was following increasingly diffuse pathways through the reservoir as testing proceeded. Geochemical data from the two test phases were similar in all respects. Logs of the production wellbore showed some slight differences in the temperatures of fluid issuing from individual fractures but no measurable difference in the average temperature of the fluid at the point where it exited the reservoir.

Cyclic Flow Testing: The two cyclic tests conducted at the end of Phase 2 of the LTFT provided new insights into reservoir management. The first test demonstrated that overall reservoir productivity could be improved by simply shutting the production well for 25 minutes on a daily basis.

The second test, which entailed shutting off the production well for 16 hours a day but injecting continuously, led to the most significant abrupt change in reservoir behavior that has been observed in 20 years of HDR research and development at Fenton Hill. At the beginning of the third production cycle of this test, the reservoir impedance suddenly declined by 50% in less than a minute. This change, which was <u>not</u> accompanied by significant seismic activity, resulted in increased production at higher temperatures during a ten-day follow-on, steady-state flow test. Unfortunately, funding constraints prevented us from conducting the thorough evaluation that this remarkable event warranted.

Interim Flow Testing: Flow testing during the interim between LTFT Phases 1 and 2 was conducted primarily to maintain system readiness while the injection pumping problem was addressed. It did provide the opportunity, however, to explore some potentially important reservoir management issues. In particular, studies of circulation at several production-well backpressures showed that a broad maximum in flow rate can be achieved over an imposed backpressure range of 9.7 to 15.2 MPa (1400-2200 psi). These results suggest that it may be possible to significantly increase the efficiency of HDR systems by operating them at a high production-well backpressure and using pressure recuperation to recover the excess mechanical energy of the circulating fluid at the surface.

Seismicity at Fenton Hill: The design of the flow test program of 1992-1993 was based on operation of the reservoir under aseismic conditions. The reservoir remained aseismic throughout the Phase 1 LTFT and into the interim flow test period, but on December 24, 1992, a small seismic event was observed. An additional 46 microseismic events were recorded over the next several months. Their occurrences were found to correlate with system shut-ins.

Reservoir Modeling Developments: Significant advancements in reservoir modeling occurred during the year. The GEOCRACK finite element model, which has been under development by Kansas State University for several years, was applied to the simulation of reservoir flow, tracer results, and transient reservoir behavior observed during recent flow testing. Good correlations with the field data were obtained. This validation of GEOCRACK by application to real results greatly increases the confidence in its predictive capability and its usefulness as a tool for the management of HDR reservoirs.

Technology Transfer: A project to evaluate the potential for development of HDR resources in the area of Clear Lake, California, came to fruition in Fiscal Year 1993 when the initial drafts of a series of reports on geothermometry, geological structure, geohydrology, seismicity, geothermal regimes and surface water hydrology in the region were completed. The reports bring together information that will be useful in planning specific HDR projects around Clear Lake. After peer review and final editing, they will be available to the general public. Work on the project, which has been under way for several years, was funded by the California Energy Commission through the city of Clearlake, California.

A number of additional initiatives were undertaken in Fiscal Year 1993 in an attempt to familiarize private industry with HDR and encourage private sector involvement in further development of HDR technology. Early in the year, a one-day session on HDR at the Geothermal Resources Council Annual Meeting in San Diego attracted an audience of well over a hundred attendees including many from private industry. At a special evening presentation, Los Alamos engineers summarized the results of flow testing up to that time to an invited group of fifty representatives of industrial firms, governmental organizations, and international HDR projects.

In January 1993, a two-day workshop on HDR was held in Philadelphia. The first day of the meeting addressed the issue of HDR for the electric power industry. It was sponsored by the Electric Power Research Institute (EPRI) and organized in large part by Professor Paul Kruger of Stanford University. The second day of the workshop was sponsored by the US Geological Survey and reviewed the prospects for the development of HDR resources in the eastern United States. This workshop brought government scientists and engineers together with a variety of personnel from private industrial firms that had been previously unfamiliar with HDR technology.

In July 1993, representatives of the Los Alamos HDR Program began participating in a series of meetings at Portland General Electric (PGE) on the subject of bringing renewable energy resources into their system. In response to a Request for Proposal (RFP) issued by PGE in the summer of 1993, a small private geothermal company, Geolectric Power Company, submitted a proposal offering to supply energy to PGE from a combination of conventional hydrothermal and HDR resources to be developed in the Clearlake, California, area. This is believed to be the first time that HDR resources were ever formally included as part of a bid to the electric power industry. The PGE-sponsored meetings eventually resulted in a series of position papers on the various renewable energy technologies. The geothermal energy paper addressed HDR technology specifically in a number of pertinent sections and discussed the potential for it to become a serious option in PGE's quest for renewable energy resources.

DOE Notice of Program Interest: In September 1993, near the end of the fiscal year, the USDOE published a Notice of Program Interest soliciting input from the private sector in regard to participation in an industry-led, cost-shared project to construct and operate a plant to produce and market energy from HDR resources. By early in Fiscal Year 1994, responses to the Notice had been received from 41 organizations including geothermal developers, alternative energy companies, utilities, engineering firms, equipment manufacturers, universities, and state energy agencies. The number of replies together with the degree of interest expressed by a number of the respondents convinced the DOE to proceed with the development of a cost-shared proposal for such a program. A formal solicitation to initiate the program will be published by the DOE early in Fiscal Year 1995.

HDR PROGRAM OBJECTIVES

The goal of the Hot Dry Rock Heat Mining Geothermal Energy Development Program is to demonstrate that HDR technology can be employed to provide a practical and economically feasible method to produce energy on a sustainable basis. In order to attain this goal, a primary objective has been formulated as follows:

Level I Objective

Develop HDR technology sufficiently by 1999 to demonstrate that power can be generated from HDR resources at costs in the range of 5-8¢/kWh.

The aim of this objective is to lead to the availability of the technical base by the year 1999 that is required to provide industry the information and incentive needed to develop commercial HDR power generation plants. In order to achieve this objective, an industry-led, DOE cost-shared HDR project to produce and market energy from an HDR resource is being formulated. Building on the flow-testing experience of 1992-1993, this joint industry-government project will entail the design and construction of a revenue-generating HDR system that will serve as a practical demonstration of the technology while at the same time helping to achieve the subsidiary objectives of the HDR program as shown below.

Level II Objectives

- Evaluate the performance of the Fenton Hill Phase II reservoir including predicted thermal lifetime, optimum, system operating characteristics, required maintenance operations, sustainable energy production, and water consumption.
- Improve the performance of drilling and completion technology under conditions typical of hot dry rock environments.
- Determine the environmental characteristics of HDR technology.
- Evaluate and optimize the economics of HDR energy production.

In order to attain the primary and subsidiary objectives in a timely manner, a set of working objectives has been developed. These are summarized as follows:

Level III Objectives

- Evaluate the large Phase II reservoir at Fenton Hill to determine its drawdown characteristics.
- Complete detailed reservoir analyses and confirm modeling of hydraulic and thermal performance of the Phase II system.
- Develop technology to monitor changes in reservoir volume and temperature, and confirm monitoring data using tracers.
- Establish reservoir-mapping techniques to locate drilling targets for production wells.
- Conduct studies on water-rock interactions and their effects on flow through a hot dry rock reservoir.
- Verify that the environmental and social consequences of HDR development are acceptable.
- Determine whether the performance of the Fenton Hill Phase II reservoir, when considered as a unit reservoir in a commercial-scale project, could support production of electricity at an economical busbar cost.
- Determine means to locate accurately the intersections of fractures with the wellbore.

BACKGROUND

The Resource

Hot springs, geysers, and erupting volcanoes provide clear evidence that the earth's interior is very hot. This heat is geothermal energy. It originates primarily in the lower crust and mantle and from the decay of unstable elements that occur naturally in the upper crust.

The earth's surface is cooled when its heat radiates into space. The outermost layers of the crust are almost the same temperature as the surface due to the cooling effects of ground water circulation. At increasing depth, the greater weight of the rock above reduces permeability and the rate of water circulation. Consequently, temperatures begin to rise.

Finally, permeability and free-water content are extremely low, the typical "hot dry rock" situation, and heat flow toward the surface is accomplished entirely by thermal conduction. The rate of heat flow is determined jointly by the conductivity of the rock and the rate at which temperature increases with depth, which is called the "geothermal gradient."

As is illustrated by Figure 1, the geothermal gradient varies widely from place to place. In the United States, it averages about 17°F per thousand feet of depth (30°C per kilometer). However, where the crust is thin or it has been disturbed by volcanic activity or large-scale earth movements, it is often much higher than that.

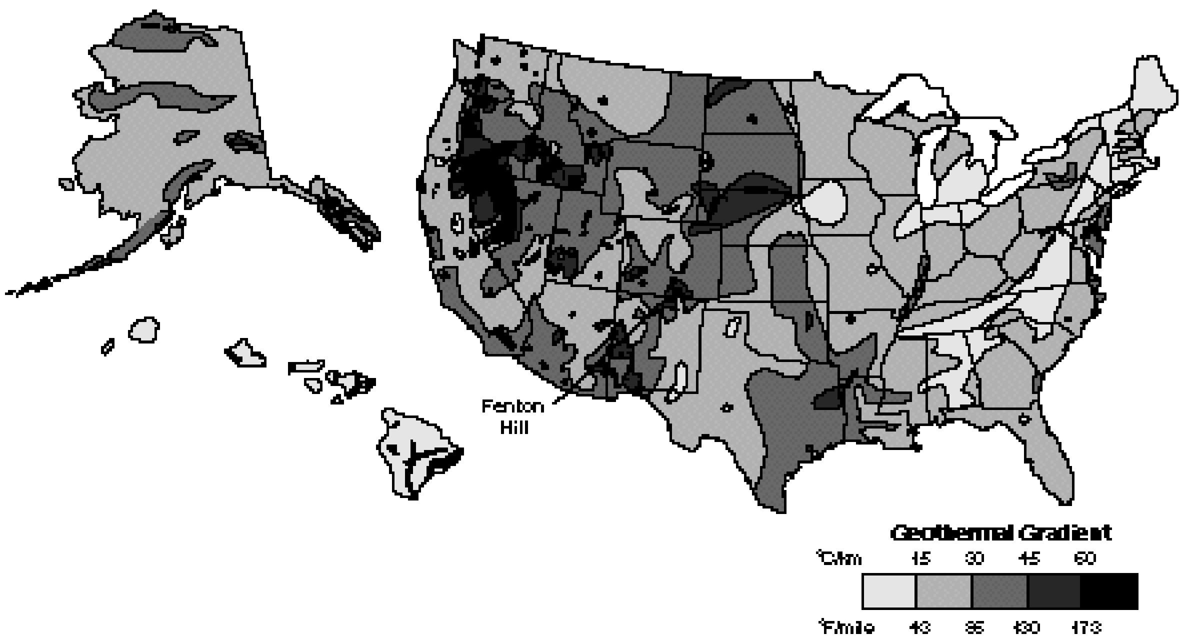


Figure 1. A geothermal gradient map of the United States. Hot rock is generally found closer to the surface in the western part of the country.

The large earth movements that create earthquakes occur by the sliding of one part of the crust past another along a fracture called a fault. This movement is usually accompanied by considerable fracturing of rock on both sides of the fault. Where the fractures have not been sealed by mineral deposition, groundwater may descend through them deeply enough to reach hot rock. Expanding as it is heated, the water rises buoyantly and may reach the surface as a hot spring, geyser, or steam vent. Or, the water may instead be trapped in porous or fractured formations called “hydrothermal reservoirs.” When these are large enough and hot enough, they can be economical sources of energy, but such occurrences are rare. At depths where temperatures are high enough to be potentially useful, the usual geologic environment is hot dry rock (HDR).

HDR exists everywhere, but at depths that vary with the local geology. Its heat content represents one of the largest supplies of energy available to man. Assuming that all heat above 25°C (77°F) is potentially useful (as is done in measuring the heating value of a fossil fuel) and that we can afford to drill geothermal wells to depths where there are temperatures high enough to generate electricity (depths of 6 kilometers or 19,700 ft are routinely reached in oil and gas drilling), then the calculated useful heat content of HDR under the United States is about 10 million quads. (One quad equals 10^{15} or one thousand trillion British Thermal Units - BTUs). In energy content, this is equivalent to about 1700 x 10^{12} (1700 trillion barrels of oil), or approximately 60,000 times the energy in the proven US reserves of crude oil.

HDR is indeed one of those essentially inexhaustible energy resources. Although HDR energy recovery involves mining heat from a body of subterranean rock, it is renewable in the sense that heat extracted from the rock will eventually be replaced by additional heat conducted to it from deeper in the earth. HDR is also a secure, broadly distributed domestic energy supply, potentially capable of significantly reducing both US dependence on imported oil and the rate at which our own fossil fuel resources are depleted.

While much of this heat is at too low a temperature to be of any practical value, one fairly conservative estimate is that there are at least 500,000 quads of useful heat in hot dry rock at accessible drilling depths beneath the US. This is about 6000 times the total amount of energy used in this country in one year. The western United States is well-endowed with high-grade HDR resources, with about 38,000 square miles of land in that category, exclusive of Alaska and Hawaii. More than 300,000 square miles of land, almost all of it west of the Mississippi, can be classified as having mid-grade HDR potential.

For the most part, however, the eastern United States possesses only low-grade HDR resources. While not currently practical for electricity generation, low-grade resources could be useful for the production of space or industrial process heat at locations where the need exists for such energy. The small space requirements of HDR plants, together with the total elimination of airborne emissions, may make HDR technology especially attractive in such applications. At the same time, improvements in drilling technology, reservoir design, and energy conversion, if diligently pursued, could rapidly make HDR resources available at competitive costs virtually everywhere.

Heat Mining

A concept for recovering useful heat from this tremendous natural resource originated at Los Alamos National Laboratory about twenty years ago. The fundamental technology involves drilling a well deep enough to reach hot rock and pumping water down the well under high enough pressure to open up natural joints in the rock. The pressurized water forced into these openings is rapidly heated to a high temperature by contact with the hot rock. In this manner, an artificial geothermal reservoir consisting of a relatively small amount of water dispersed in a large volume of hot rock is created.

One or more additional wells are then drilled into the reservoir at some distance from the first to tap this pressurized hot water and bring it to the surface for practical use. After its thermal energy has been extracted, the same water is pumped back into the hot rock to recharge the engineered geothermal reservoir. In this closed-loop process, nothing except waste heat is released to the environment and no long-term wastes accumulate. Figure 2 is an illustration of a typical HDR heat mine.

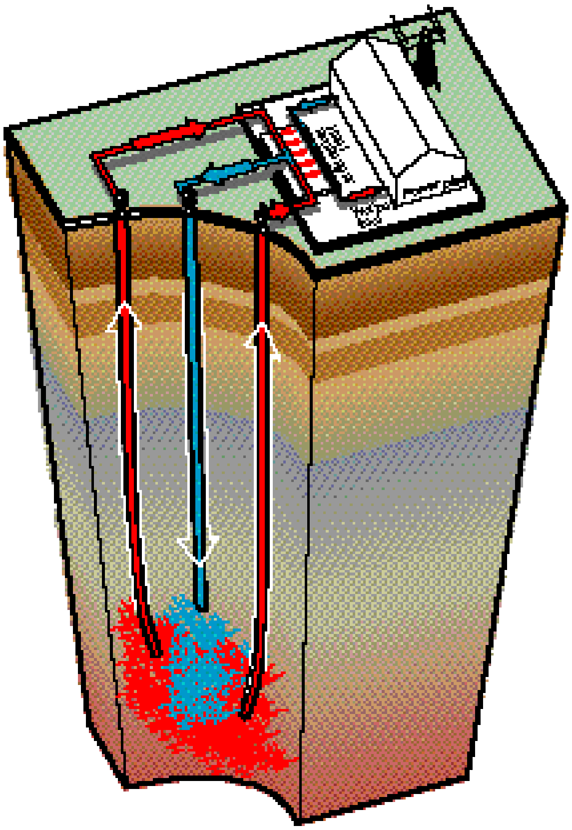


Figure 2. Conceptual drawing of a hot dry rock geothermal heat mine. In operation, the same water is continually recirculated around the heat extraction loops.

Work to develop HDR technology based on the above concept began in the 1970s. Background studies and field investigations showed that useful hot rock is present at accessible drilling depths under most of the United States. Much of the technology required to construct the proposed system already existed in the petroleum and natural gas industries. Accordingly, a Hot Dry Rock Geothermal Energy Development Program, sponsored by the division of Geothermal Technology of the US Department of Energy and its predecessor agencies, was established at Los Alamos National Laboratory. The primary objective of this program has been to develop the engineering technology and scientific understanding that will make commercial development of hot dry rock (HDR) geothermal energy systems practical and economical.

An HDR energy system is self-sufficient and therefore not subject to shutdowns as a result of interruptions in its fuel supply by storms, strikes, or political disturbances. Being completely contained, it will have little or no adverse environmental effect and, requiring no surface area for fuel or spent-fuel storage, waste dumps, or transportation facilities, its land use will be small.

The broad distribution of the energy source provides great flexibility with regard to the location of HDR energy systems. They can be built where there is little or no problem with land acquisition and where long distance transmission lines—and the large land use and scenic disruption that they involve—will not be necessary. To the environmentally concerned, HDR offers a welcome alternative to almost all other energy systems.

Finally, an HDR system does not have to be extremely large in size to be economically viable, and its surface system is relatively simple. It can be constructed rapidly in modular units almost anywhere that energy is needed. In a time of uncertainty with regard to future energy demand and cost, this can greatly reduce the financial risk otherwise incurred by construction of traditional power plants, which typically are very large and enormously expensive.

Costs of Energy from HDR

Field Test Data: Flow testing during 1992-1993 demonstrated that significant amounts of energy could be produced on a continuous basis from the HDR reservoir at Fenton Hill, New Mexico, and measurements showed that the energy output of the plant was several times the amount of energy required for its operation. While these field-testing results provide important evidence that HDR resources may be viable for energy production, the do not directly address the economics of the technology. Until a plant designed specifically to produce and market energy from HDR comes on line and both capital and operating costs can be well-documented, economic analyses based on reasonable assumptions will provide the best available measures of the potential costs of energy from HDR. An industry-led project to construct and operate a facility to produce and market energy from HDR resources is scheduled to be initiated in 1995. That project will present the first opportunity to obtain hard data on the economics of energy production from HDR.

Studies of HDR Economics: A number of independent cost studies of HDR have been conducted over the past twenty years. The Los Alamos National Laboratory, the Electric

Power Research Institute, Meridian Corp., Bechtel National Inc., the United Kingdom Department of Energy and the Japanese evaluated the economics of HDR during the 1970s and 1980s. The results of all these studies were used by Tester and Herzog of the Massachusetts Institute of Technology Energy Laboratory in 1990 to prepare a composite picture of the economics of HDR heat mining. The MIT work indicated that a 50 MW power plant drawing on a series of two-well HDR systems of the general type already in place at Fenton Hill, New Mexico, could generate electricity at busbar costs of 5-6¢/kWh from high-grade resources, 8-9¢/kWh from medium-grade resources, and 16-18¢/kWh from low-grade resources.

The study further estimated that by designing HDR plants with reservoir modules penetrated by three wells, one injector and two producers, the costs of electricity production could be reduced to 3-4¢ at high-grade resource locations. Reservoir engineering studies based on flow testing at Fenton Hill in the United States and at Hijiori in Japan (where an HDR system with one production well and several production wells has actually been developed) have led to a consensus among HDR specialists that the first practical application of HDR technology will be likely to utilize a system with more than one production well per injection well.

In a 1993 study conducted for the USDOE, Ken Pierce of Sandia National Laboratories and Bill Livesay, a private consultant, evaluated the cost of producing electricity from a relatively small HDR plant. They estimated that the capital costs for a plant capable of generating a net power output of 5.1 MW using binary conversion technology would be about $6,200 per installed kW, including drilling, reservoir development, and surface plant costs. They further estimated that the operating and maintenance costs for such a plant would run about 4.0¢/kWh. Their study envisioned a facility with two production wells and one injection well. A resource with a moderately high gradient was specified, similar to the Fenton Hill HDR site and typical of what might be found at numerous locations in the western US.

Techniques to Increase the Productivity of HDR Systems: The cost studies cited above were based on the implementation of HDR technology by means of the most efficient drilling, reservoir development, and energy conversion techniques commercially available today. They did not, however, consider some unique resource and technology aspects of HDR that might significantly improve its position in the competitive energy marketplace.

For example, HDR reservoirs require the application of very high pressure to force open joints in the earth, but a much lower pressure differential between the injection and production wells is sufficient to move the circulating fluid through the opened joints. In conventionally designed HDR plants, the excess mechanical pressure of the circulating fluid is lost when the pressure is reduced at the production wellhead prior to thermal energy extraction in the surface plant. All that lost mechanical energy has to be restored by the injection pump prior to reinjection of the fluid. Pressure recuperation equipment could be applied to capture and use the excess mechanical energy now wasted at the surface or, alternatively, a high-pressure surface plant could be designed to deliver highly pressurized fluid to the injection pump and thereby reduce the net energy required for reinjection.

The closed-loop nature of HDR systems also makes them much more amenable to engineering innovations than conventional hydrothermal plants. Cyclic operating schedules may be feasible in which the reservoir is charged with fluid at times of low energy demand when costs are low, and energy is produced from the reservoir during peak usage hours when the power has much more value. As discussed in other parts of this report, variations of cyclic operating schedules have recently been shown to be effective in increasing overall reservoir productivity. In addition, additives to the circulating fluid such as carbon dioxide may actually be capable of providing a gas boost which can further increase the efficiency of the circulation process.

HDR systems are also amenable to unique cogeneration schemes. It is easy to envision wastewater from industrial or municipal sources, or even seawater, as the feedstock for a plant combining energy generation with water purification. Such dual use applications may provide the competitive edge for HDR technology in countries that are deficient in both water and fossil fuel resources.

These novel concepts for increasing the productivity of HDR systems have so far gone largely untested, but their potential for improving the economics of HDR energy production is very significant. As HDR technology is implemented over the next few years, every opportunity to evaluate these techniques under realistic operating conditions should be pursued.

International HDR Activities

US Interactions: The abundant HDR energy supply is, of course, not confined to the United States. It is a worldwide resource and is attracting increasing international interest. Under an International Energy Agency (IEA) agreement, agencies of the governments of Germany and Japan, KFA-Julich and the New Energy Development Organization (NEDO) participated directly in the Fenton Hill Project during 1980-1986. Their participation involved partial financial support, membership on an International Steering Committee, and long-term assignment of scientists and engineers from both countries to the HDR staff at Los Alamos. Under bilateral agreement between the US DOE and the Italian Energy Agency (ENEL), a close relation with geothermal programs in Italy was established.

Japan: Japan currently has two significant HDR field projects. At both locations, work is suspended during the winter months due to a combination of harsh weather conditions and poorly developed access to the sites. NEDO has been working at Hijiori in northern Honshu since 1986. Using an abandoned hydrothermal test well as an injection well, they developed an HDR reservoir at a depth of about 1.8 km (5,900 ft) in rock at a temperature of about 250°C (480°F).

The original Hijiori reservoir was considerably different than the Fenton Hill reservoir in that it extended into an open fault. During a 90-day flow test in 1992, circulation rates in excess of 500 gpm were achieved at Hijiori at injection pressures of only about 3.4 MPa (500 psi) (in contrast, at Fenton Hill, pressures on the order of 27.6 MPa (4,000 psi) are required to circulate about 100 gpm through the reservoir).

Even with the utilization of three production wells penetrating the reservoir at well-separated points, water loss rates during the flow test were more than 20% of the injected volume. A well connected to the open fault produced the largest volume of fluid. It is also worth noting that the Hijiori system was not operated in a closed-loop mode. The produced fluid was delivered to a separator where the volatile fraction was flashed off as steam. The residual hot water was pumped through a heat exchanger to a storage pond. Water from the pond and a nearby stream supplied the injection fluid.

Recently, the Japanese have created a new HDR reservoir at Hijiori centered at a depth of 2.2 km (7,200 ft). The reservoir is penetrated by the three former production wells, but the original injection well has been abandoned. Reservoir evaluation studies and preliminary flow tests of the deeper Hijiori reservoir are scheduled for the summer of 1994, with long-term flow testing set for 1995.

The Central Research Institute for the Electric Power Industry (CREIPI) operates its own HDR research site at Ogachi, also on the island of Honshu but somewhat farther north than Hijiori. A reservoir was established at the site several years ago at a depth of 1 km (3,300 ft) in rock at about 200°C (390°F). In 1993, a second reservoir was established from the same wellbore at a depth of only 700 m (3,300 ft) using a “sand and ream” technique developed by CREIPI for creating the multi-reservoir systems that they believe will be necessary for the efficient extraction of energy from HDR. Although they were created from a single wellbore, the Ogachi reservoirs tended to propagate in different directions, and it was necessary to drill a production wellbore in a somewhat tortuous path to penetrate both of them. In November 1993, the first production from the two-reservoir system was achieved. Plans called for a 5-month flow test during 1994.

Europe: The United Kingdom has been deeply involved in HDR research since 1978. Their experimental site in Cornwall has a relatively low thermal gradient of about 35° C/km. In 1989, a conceptual design study concluded that the development of a commercial HDR system at that location would not be economically feasible with today’s HDR technology. The British thus decided to de-emphasize underground work in Cornwall and take a more active role in other western European HDR projects with an eye toward future participation in a major HDR development effort under the auspices of the European Community.

While some HDR work has recently been under way at Bad Urach in Germany, it is now clear that HDR work conducted under the auspices of the European Community will be concentrated at Soultz, a site in the Rhine Graben in northeastern France about 35 miles north of Strasbourg. The major participants in the European project are France, Germany, and the United Kingdom, but researchers from Sweden, Switzerland, and, more recently, Italy have also been involved in work at Soultz. The first well was sunk at Soultz in 1989. It was originally drilled to 2.0 km (6,600 ft) where a small hydrothermal system was intersected, but in late 1992 it was deepened to about 3.6 km (11,800 ft). The rock temperatures at the latter depth were found to be in the range of 160-170°C (320-340°F).

Field work at Soultz has been largely confined to fracturing, seismic, and geochemistry studies because a circulation system has not yet been established. An attempt to develop a second wellbore several years ago failed due to drilling problems. That hole is now used for seismic observations. Plans are now being formulated to drill another well in 1994. It will be located about 200-400 m from the current deep borehole and extend to a depth of 3.5-4.5 km (11,500-14,800 ft). The completion of a functional two-well HDR system appears essential if the European HDR program is to move forward.

Russia: Significant HDR work was also conducted in Russia a few years ago. Drilling and fracturing operations were carried out at Tirniaus near Elbrus in the Caucasus Mountains. The experimental work followed the Fenton Hill model with drilling to 3.6 km (11,800 ft) followed by fracturing operations at pressures up to 60 MPa (8700 psi). Mechanical problems led to abandonment of the deepest portion of the original wellbore. Sidetracking to another location at the same depth and further fracturing were planned, but the confused political and economic situation in Russia seems to have brought the project to a halt. The Russian program could be greatly enhanced by some of the advanced technologies developed at Fenton Hill. Under the right conditions, joint US-Russian cooperation could lead to significant benefits for both parties.

Other Areas: Renewable-energy technologies have excellent export potential in the developing countries. Penetrating these markets, and holding domestic markets in the face of rising foreign competition, depends on continuing technical progress driven by advanced research. The development of a technology base, upon which industry can build, will involve a sustained research commitment well in advance of potential payoffs. Continued research progress by the public sector in tandem with private sector development initiatives will speed the widespread application of renewable energy technologies.

The nation or nations that are leaders in the development and commercialization of HDR will take a large step toward energy independence, make significant advances in solving their environmental problems without sacrificing vital energy consuming activities, and create a large domestic and foreign market for their drilling and related services industries. For all of these reasons, the DOE-sponsored Hot Dry Rock Geothermal Energy Development Program is important to the United States and the rest of the world.

HISTORY OF HDR RESEARCH AND DEVELOPMENT

The Phase I System

Although other methods of energy recovery are potentially useful in other geologic environments or for other purposes, the Hot Dry Rock (HDR) Program has so far concentrated on the common case of hot crystalline rock of low initial permeability; the use of fluid pressure downhole (hydraulic fracturing) to create flow passages and heat-transfer surfaces within the rock; and the operation of a recirculating, pressurized-water loop to extract heat from the rock and transport it to the surface. At the surface, the useful heat is recovered through heat exchangers, and the cooled water is reinjected to recirculate through the fractured rock and recover more heat from it.

This HDR geothermal energy concept originated at the Los Alamos National Laboratory in 1970. Background and field investigations between 1970 and 1974 were encouraging with regard to the practicality of developing hydraulically fractured HDR systems. An area about 35 km (21 miles) west of Los Alamos that appeared to be well suited for large-scale HDR field experiments was identified by air. At Fenton Hill, a convenient location within that area, the world's first HDR energy system was completed in 1977. It was enlarged in 1979 by additional hydraulic fracturing and operated successfully for more than a year.

This "Phase I" or "Research" system extracted heat from hydraulically fractured granitic rock at a depth of about 3000 m (9850 ft), where the initial rock temperature was around 185°C (365°F), and brought it to the surface in pressurized water at 135° to 140°C (275° to 285°F) at rates up to 5 MWt (thermal megawatts) or about 17 million BTU/hr. Some of the heat was used to operate an experimental binary cycle power plant which produced 60 kW of electricity that was used at the site. System operation was essentially trouble-free, and there were no detectable scaling, plugging, corrosion, or environmental effects.

Successful completion and operation of the Phase I system at Fenton Hill accomplished the original goal of the HDR Program. In a populated area, it could have heated several hundred homes for many years, and it demonstrated the engineering feasibility of HDR energy systems. However, it did not produce heat at a temperature or rate that would support economical operation of a commercial electricity-generating power plant in competition with fossil fuel or nuclear energy plants. Since higher temperature HDR systems had the potential to do so and a worldwide need existed for clean alternative energy supplies, the HDR Program was extended to attempt to meet those more demanding requirements.

The Phase II System

Development: Under this new directive, construction of a larger, deeper, and hotter "Phase II" or "Engineering" HDR system began at Fenton Hill in 1979. Two new wells about 50 m (150 ft) apart at the surface were drilled, the deeper one to a vertical depth of 4390 m (14,400 ft) where the rock temperature was 327°C (620°F). From hydraulic-fracturing theory and experience in creating the Phase I system, it was expected that hydraulic fractures produced in the Phase II system would be substantially planar and vertical, with an approximately north-northwest strike. Therefore, to provide the horizontal separation needed to thermally isolate a series of such fractures, the bottom 1000 m (3280 ft) of the first well was drilled toward the east-northeast and inclined at 35° to the vertical. The second well was then directionally drilled with its inclined section 380 m (1250 ft) vertically above that of the first well as illustrated in Figure 3a.

Hydraulic fracturing experiments were conducted at various depths in these two wells during 1982, 1983, and 1984. Unexpectedly, the fracture systems produced were three-dimensional rather than planar, inclined rather than vertical, and did not meet each other or connect the two wells hydraulically. This fracturing behavior is probably the result of a joint pattern in the reservoir rock that is related to the presence of a cooling magma body underlying a volcanic caldera a few kilometers east of Fenton Hill. Because it appeared unlikely that further hydraulic fracturing would establish the required connection, it was concluded that a more promising approach would be to redrill one of the wells directionally through a fracture system created from the other well.

The largest of the potential redrilling targets was the fractured volume produced in December 1983 by the Massive Hydraulic Fracture (MHF) Experiment during which 21,300 m^3 (5.63 million gallons) of water was pumped at 48 MPa (7000 psi) pressure into an isolated section of the deeper well, in the depth interval 3529 to 3550 m (11,580 to 11,650 ft). The target volumes were based on the locations of microearthquakes determined from analyses of records of the seismicity that occurred during the MHF Experiment

Accordingly, during the spring of 1985, the upper well was sidetracked at a measured depth of about 2830 m (9285 ft) and completed to a final depth of 4018 m (13,182 ft), where the rock temperature was about 265° C (510°F). The sidetracked well did intersect several of the fractures produced by the MHF operation, which provided good flow connections to the lower well from which they had been produced. These fractures and the two wells constituted the Phase II underground heat-extraction loop. The lower well was later redrilled, as discussed below, to create the present Phase II system shown in Figure 3b.

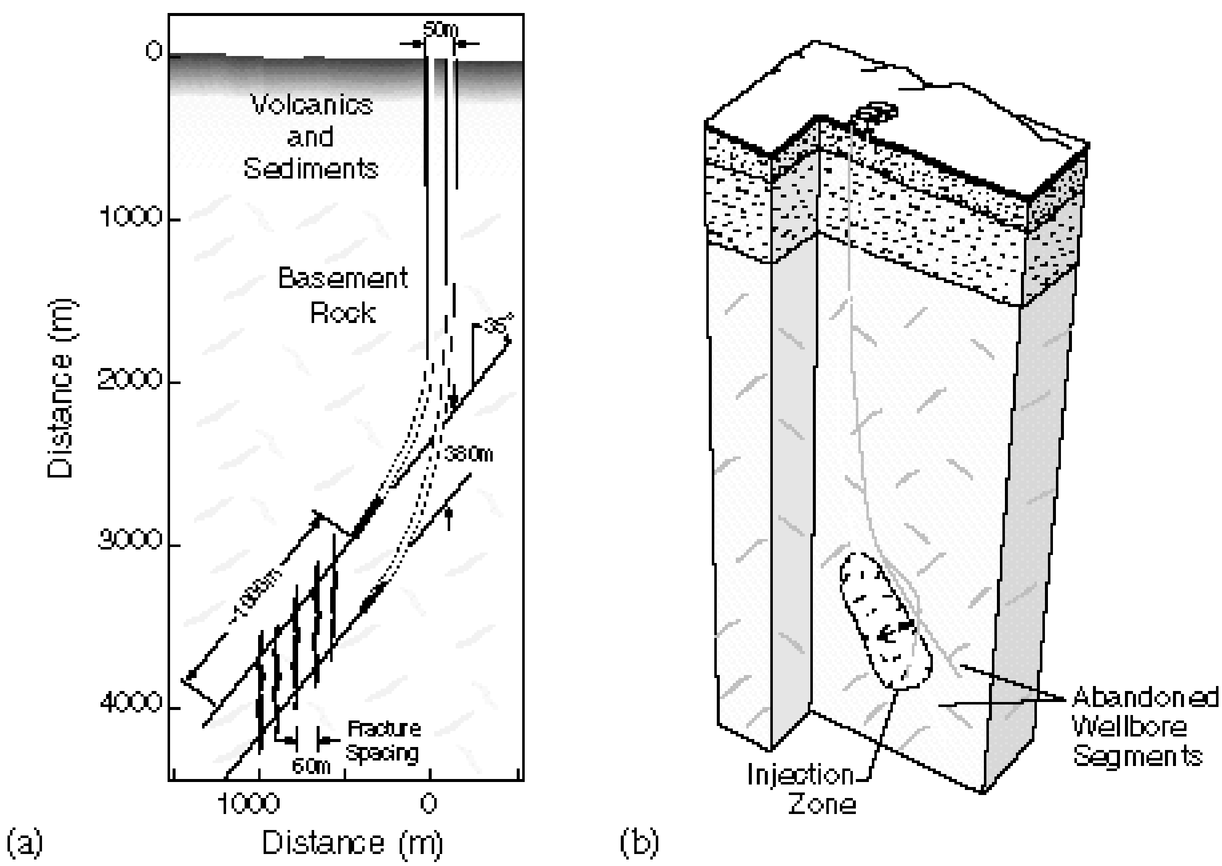


Figure 3. (a) Original conceptual design of the Phase II HDR reservoir.
(b) View of the actual Phase II HDR reservoir.

i**Initial Flow Testing:** After several preliminary experiments, an Initial Closed-Loop Flow Test (ICFT) of the Phase II system was conducted over a period of thirty days in May and June 1986. A total of 37,000 m^3 (9.76 million gallons) of cool water was injected through well EE-3A, of which 66% was recovered through the production well, EE-2, during the test, and an additional 20% was recovered during a subsequent venting operation from temporary storage in the pressurized fracture system.

Pumping rates were usually either 10.6 or 18.5 l/s (168 or 295 gpm) at surface pressures of about 26.9 MPa (3900 psi) and 30.3 MPa (4400 psi), respectively. To prevent boiling of the superheated water or evolution of carbon dioxide gas entrained in the fluid, a back-pressure of about 3.5 MPa (500 psi) was maintained on the production well. Fluid production rates were 6.3 to 13.9 l/s (100 to 220 gpm).

As illustrated in Figure 4, results of the ICFT were uniformly encouraging. Over the course of the thirty day test, the temperature of the produced fluid increased to about 200°C (390°F), and the rate of energy production increased correspondingly to nearly 10 MWt (34 million BTU/hr). Overall flow impedance through the fractured reservoir decreased during the test. The recovery rate of injected water increased with time under conditions of constant pressure and was continuing to improve at the close of the test.

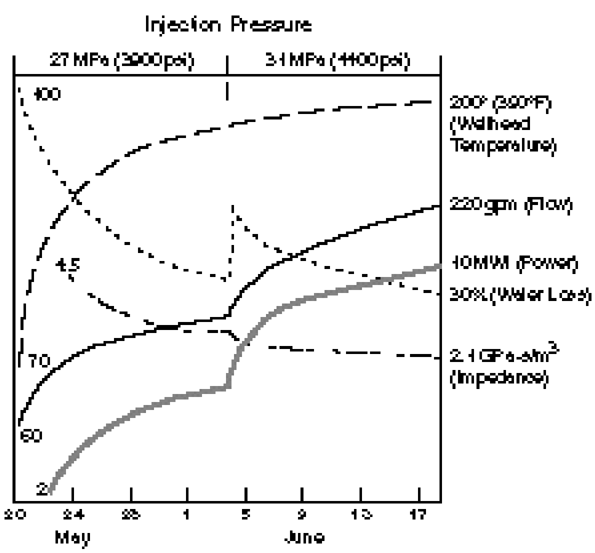


Figure 4. Results of the Initial Closed-Loop Flow Test of the Phase I HDR reservoir.

Additional Wellbore Modifications: As a result of fatigue failure of a flow-line connection to well EE-2, an uncontrolled vent had occurred that led to the termination of the MHF in 1983. The venting created leaks in the lower part of the 245 mm (9 5/8 in.) casing and an obstruction in the 178 mm (7 in.) transition liner below the casing. Removal of the upper sections of the liner as well as caliper logs and impression block runs in November 1986 showed that both the liner and the casing had partially collapsed at a depth of about 3200 m (10,500 ft).

The ICFT had been successfully conducted with the system in this impaired condition, but it was thought that the wellbore would continue to deteriorate during extended testing. Attempts to mill out the obstruction and re-enter the remaining liner were unsuccessful, and several other options for repairing the well were considered.

In January 1987, the Geothermal Technology Division of the DOE convened a panel of drilling and well-completion experts to explore solutions to the problems at Fenton Hill. In accordance with their recommendations, the HDR Program opted to seal the casing leaks and add support to the upper part of the casing by cementing the annulus behind it. The well was also to be sidetracked and redrilled from a point above the region of casing collapse.

A drilling rig was mobilized over well EE-2 in early September 1987 to conduct these operations. The bottom of the well was plugged with cement to prevent interactions with the redrilled wellbore and provide a base for subsequent installation of the whipstock needed for sidetracking. The annulus behind the casing was filled with cement to the level of a lost circulation zone at about 735 m (2510 ft) in depth, and casing leaks and perforations were sealed with high-strength cement. A window for sidetracking the well was produced by milling out the casing from 2953 to 2971 m (9688 to 9747 ft).

In Fiscal Year 1988, a whipstock was installed and the well was successfully sidetracked. The redrilled wellbore was redesignated as EE-2A. It required just 30 days to drill 800 m (2600 ft)) of additional well, an average drilling rate of 27 m (87 ft) per day, which is two and one-half times faster than was achieved during the original drilling of the well in 1978-1979. As a consequence of this favorable experience, HDR researchers believe that if the entire well were redrilled today, its cost would be only $4 million rather that the $10 million actually spent. This brightens the future of HDR and other geothermal programs because a 60% saving in drilling costs corresponds to at least a 10-20% reduction of the overall costs to generate electricity.

Static Pressurization Testing: A potential major obstacle to the long-term testing of the Phase II system was resolved by a long-term pressurization test of the Phase II reservoir during 1989-1991. The rate at which water is irrecoverably lost to the underground rock in the operation of HDR geothermal extraction systems has been a major source of concern in areas of the country where surface water is a limited resource.

At Fenton Hill, the rate of water loss, which had been measured during transient flow tests, including the ICFT noted above, would have been unacceptable for the long term operation of the Phase II system or others like it in the arid west. Subsequent measurements of water loss conducted under steady-state conditions during long-term pressurization have shown that the water loss rate during operation of the reservoir should be much less than earlier estimates based on transient measurements.

As shown in Figure 5, the water required to keep the Phase II reservoir at Fenton Hill at a constant level of pressurization has been shown to decline linearly with the natural logarithm of time as microcracks in the reservoir rock become saturated. Eventually, water consumption reaches a very low rate, indicative primarily of water leakage from the periphery of the reservoir. This important finding provides strong evidence that excessive water consumption will not be a major problem during sustained operation of HDR systems in low-permeability basement rock.

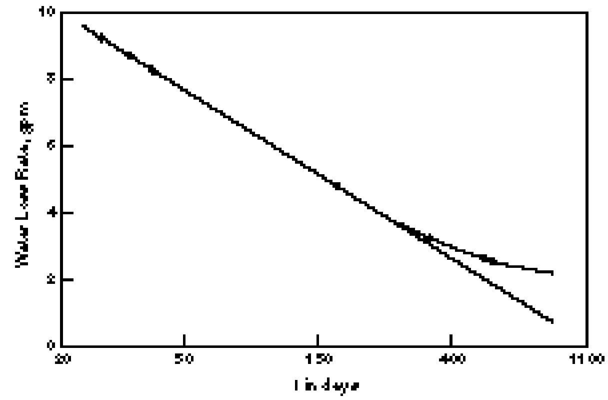


Figure 5. The water required to maintain the HDR reservoir at a constant pressure of 15 MPa (2180 psi) declined linearly with the natural logarithm of time.

Surface Plant Construction and Commissioning: Construction of the surface plant required for continuous operation of the Fenton Hill HDR system was essentially completed in late 1991. Figure 6 is a sketch showing the layout of the surface plant. Figure 7 is a flow diagram of the facility. The system was constructed to power plant standards and completely automated. The most important data acquisition and control points in the surface loop are shown in Figure 8. With plant construction essentially complete, 1992 began with the Fenton Hill facility ready for plant commissioning and flow-test operations.

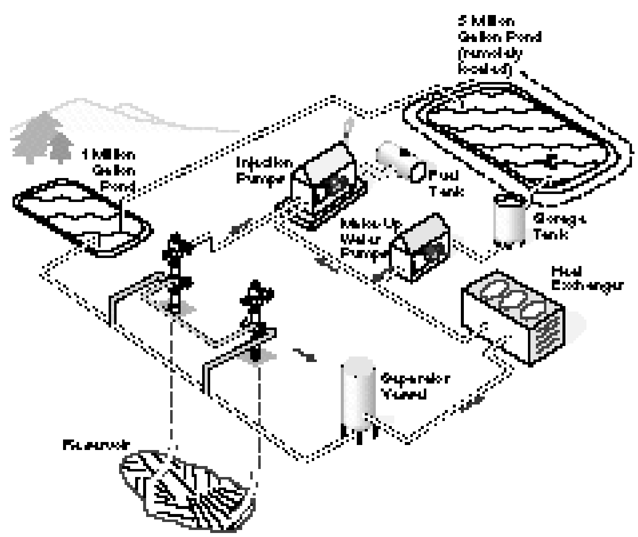


Figure 6. The Fenton Hill HDR surface plant (not to scale).

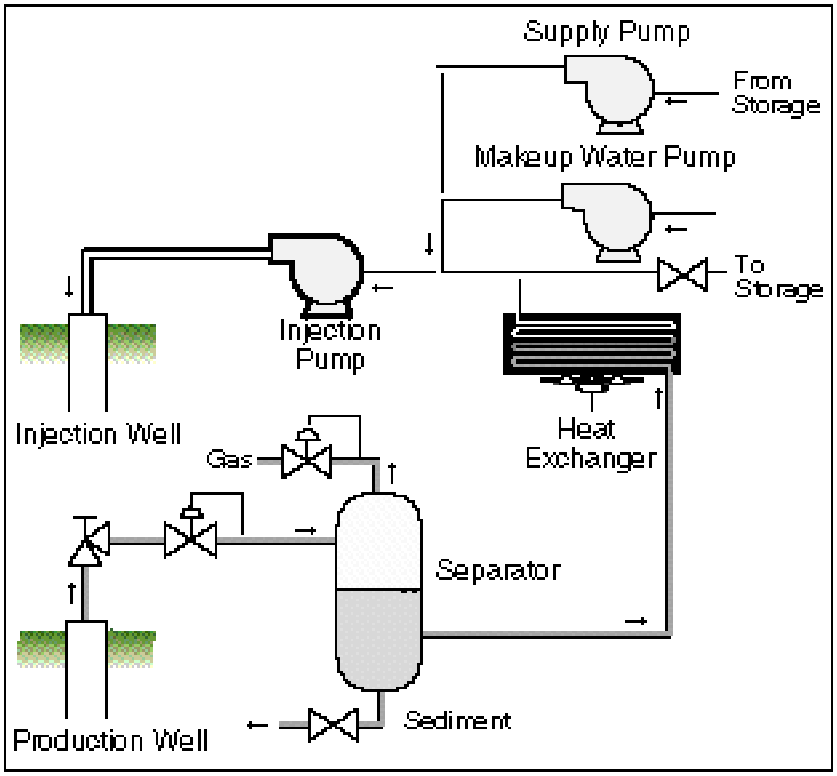


Figure 7. Flow diagram of the Fenton Hill HDR surface plant. The system is normally operated in a closed-loop mode with water constantly recirculated through the underground reservoir.

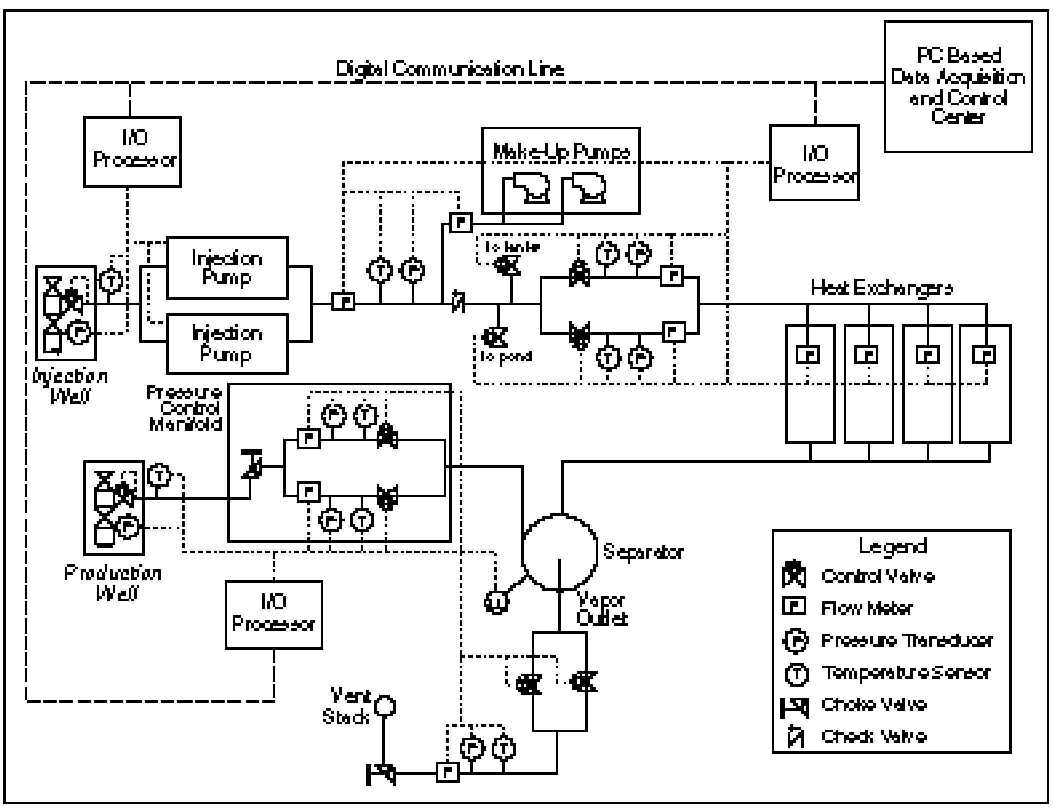


Figure 8. The Fenton Hill HDR plant is fully automated with numerous control and data acquisition points.

After a minor problem with one of the injection pumps was corrected, a four-day fluid-circulation test was run in early December. All major plant components performed adequately, but a few minor operational problems were identified and addressed. Then a second four-day test was run in early February 1992. At the end of that test, a short experiment was conducted to evaluate the feasibility of maintaining a 0.6 to 1.2 l/s (10-20 gpm) production flow to protect the surface equipment from freezing when the system was shut down for any reason during the winter. This was successful and by the end of Fiscal Year 1992, the plant control system had been programmed so that this low-flow operating mode was initiated automatically whenever a plant shutdown occurred.

To test the plant under a variety of realistic operating scenarios, a third shakedown test was run late in February. In part of this test, loss of electric power to the site was simulated in order to verify that specially designed control functions would act to shut down the surface components in the proper order. It performed as planned, and did so repeatedly on later occasions when there were unanticipated power outages.

By the first of March, all system components appeared to be functioning as designed. Therefore, in what was intended to be the beginning of the LTFT, continuous, around-the-clock operation of the circulation system was initiated on March 3. The surface system performed satisfactorily except that thermal expansion resulted in slow growth of the production-wellhead piping. By March 13 it appeared that this could lead to excessive bending of some of the piping and put excessive stress on some surface components. The system was therefore shut down and an expansion section was designed, fabricated, inspected, and installed. Flow testing was resumed on April 8, and there were no further thermal-expansion problems.

Long-Term Flow Testing

Phase 1 Test Results: From April 8 to July 31, 1992, water was circulated through the system 24 hours a day with only a few short interruptions due to electrical power outages.

As is illustrated by Figure 9, the injection pressure was maintained at the highest level that would not cause fracture extension--approximately 27.3 MPa (3960 psi), and pressure in the production well was kept at 9.7 MPa (1400 psi) to prevent boiling of the superheated water, keep dissolved gases in solution, and dilate flow passages in the reservoir region near that wellbore.

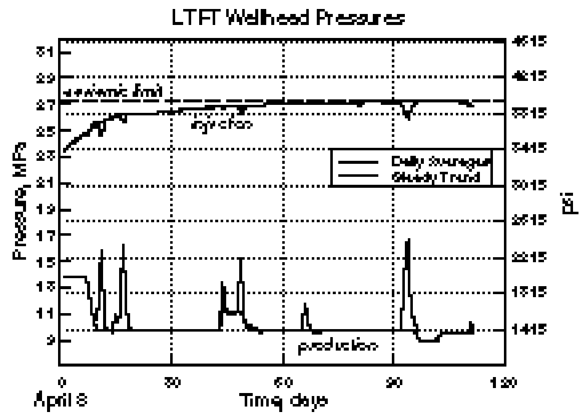


Figure 9. Wellhead pressures during the LTFT. The injection pressure was maintained at the highest possible aseismic level. A backpressure of about 9.7 MPa (1400 psi) was typically maintained on the production well.

No microearthquakes were detected during this test period, indicating that there was no fracture extension as a result of pressurization of the reservoir. However, there was a 23% increase in the total volume of fluid contained in the reservoir, evidently resulting from thermal contraction of the reservoir rock as heat was extracted from it.

Figure 10 shows the results of tracer tests conducted on May 18, somewhat more than a month after LTFT Phase 1 was initiated, and on July 7, near the end of that circulation period. During the May test, tracer was detected in the produced fluid 3.5 hours after it was injected, and the tracer concentration peaked at about 11 hours.

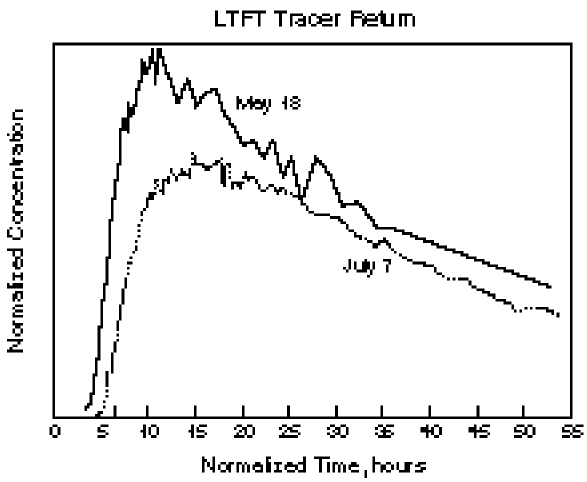


Figure 10. A tracer injected in July took considerably longer to pass through the HDR reservoir than a similar tracer injected in May, indicating that the flow within the reservoir had become redistributed to more indirect pathways between the wellbores.

In the July test, the first return of tracer was not observed until about 5 hours after injection, and peak concentration occurred at about 16 hours. These changes indicate a redistribution of flow through the reservoir between May 18 and July 7. About 6% of the produced fluid that had traveled more or less directly between in the wellbores in May was flowing through more circuitous, longer residence-time, flow paths in early July.

The tracer tests also showed that, between May 18 and July 7, the fluid volume in the reservoir increased from 2246 to 2766 cubic meters (593 to 731 thousand gallons), perhaps due to thermal contraction of the cooling rock. The apparent rate of water loss declined with time over the four-month test period, averaging 11% of the injected fluid. However, about 17% of this was actually increased storage in the new void volume created in the reservoir. As is indicated by Figure 11, in spite of a small increase in injection pressure during the course of the flow test, both the injection and the production flow rates decreased.

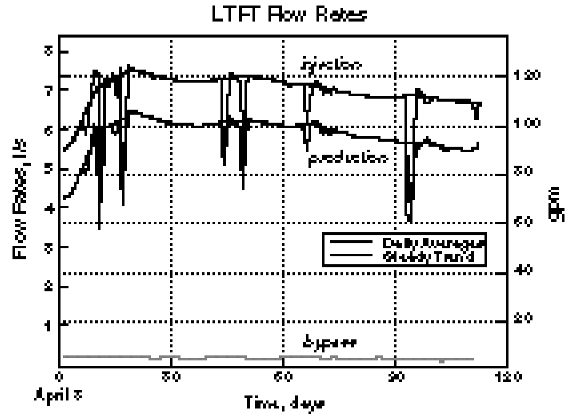


Figure 11. Injection and production rates declined about 10% over the course of the LTFT. The bypass flow is due to a leak from the reservoir to the annulus of the injection wellbore.

Although new flow paths had opened, overall flow impedance through the reservoir had increased. Evidently, that increase occurred in the preexisting, more direct connections between the wells. At least in part, this can be explained by cooling of the fracture surfaces along those paths and the resulting increase in viscosity of the cooler water flowing through them. If a reduction in temperature of fluid flowing through some pathways did occur, it was apparently compensated by the higher temperature of fluid following new flow paths through other portions of the reservoir which had not been cooled, and there was no change in the mean temperature of fluid entering the production wellbore. This is encouraging with regard to the probable useful life of an HDR reservoir.

Failure of the injection pumps terminated LTFT phase 1 on July 31, 1992. Energy production had been maintained at an average level of about 4 thermal megawatts and the on-line availability factor was 98.84%. There was no evidence of thermal drawdown in the produced fluid.

After the LTFT was shut down, circulation through the system was continued until October 1, 1992, using a limited-capacity reserve pump on hand at Fenton Hill for fluid injection. This was primarily to maintain the thermal stability of the injection and production wellbores, and was done at lower injection pressures and flow rates than those established for the LTFT.

Technology Transfer

Industry has been directly involved in the HDR Program from its beginning. All the drilling and completion work at Fenton Hill during the 1970 and 1980s was performed by private companies under contract. Novel drilling and coring bits, downhole motors, open-hole packers, and other equipment developed specifically for the HDR program have now found uses throughout the drilling industry. Logging instruments initially designed for use at Fenton Hill have also been widely adapted by the conventional geothermal, oil, and gas industries. Finally, the seismic techniques that were refined and brought to a high degree of sophistication in an attempt to understand the HDR reservoir at Fenton Hill are now being applied around the world to evaluate oil and gas reservoirs and develop methods for more efficiently recovering these fossil resources.

In recent years, the focus of HDR technology transfer has shifted away from spin-offs of products and techniques developed as adjuncts to research and development activities, and toward the privatization and commercial implementation of the fundamental HDR energy production technology. Several industry advisory panels were convened to help develop a protocol for the long-term flow testing program of 1992-1993. Based on the advice of these panels, the test protocol was designed to provide answers to the questions private industry considered most critical to the successful commercialization of HDR technology.

During Fiscal Year 1993, as discussed later in this report, formal agreements to promote the private development of HDR technology were reached with several organizations and the stage was set for the initiation of an industry-led effort to construct and operate a plant that would produce and market energy derived from an HDR resource.

PROGRESS DURING FISCAL YEAR 1993

Overview

Continuous operation of the Fenton Hill HDR Test Facility was successfully resumed in the second quarter of Fiscal Year 1993 when the diesel-driven pumps originally used to inject water into the large HDR reservoir were replaced with a rented, electrically powered centrifugal pump. Locating the pump, assessing its suitability for use at Fenton Hill, and procuring it took approximately 6 months, so that it did not arrive at Fenton Hill until mid-January 1993 (the diesel pumps had broken down and the long-term flow test (LTFT) had been suspended at the end of the previous July). About another month was spent on installation, including adding significant new electrical capacity at Fenton Hill, so that it was mid-February by the time full-scale, continuous flow testing got re-started.

Testing then continued on an around-the-clock basis for 55 days until April 17 with essentially no problems until funding constraints made it necessary to shut the system down. Although the injection pump was scheduled to be returned to the lessor before the end of April, a special arrangement was reached that allowed us to keep it an extra month at a fraction of the normal rental rate. This gave us the opportunity to conduct some additional flow testing during May.

Results of this second LTFT segment (known as LTFT Phase 2) were in every way consistent with those of the 112-day segment (LTFT Phase 1), and observations and experiments before, during, and after this second operational phase provided important new information about the nature and behavior of the large Phase II HDR reservoir. All of this is discussed in the sections of this report that follow.

Reservoir Operations

System Maintenance Pumping: Interim flow testing that had been under way at the close of Fiscal Year 1992 was suspended on October 2, 1992, due to breakdown of the old backup injection pump that had been pressed into service on an ad hoc basis when the primary injection pump failed in late July. A replacement mud pump was installed on October 28, by which time static pressure in the reservoir had declined from 19.3 MPa (2800 psi) on October 2 to 15.2 MPa (2210 psi). With this replacement pump, pressure was raised slowly—but with many brief shutdowns caused by minor pump problems and by two interruptions of power to the site caused by severe winter weather. As a result, there were no extended periods of continuous energy production during October or November.

When the rental injection pump had once again been repaired, the flow test was resumed on December 4. It continued until December 16, when an electrical supply problem caused the heat-exchanger fan to shut down. This was soon corrected, but freezing of a heat-exchanger bundle and some minor mechanical problems delayed restarting the system until December 18. Flow testing was then resumed and continued until the rented mud pump failed irreparably on January 3, 1993. During two flow-testing intervals in December, equilibrium operating conditions were established at two different production-well backpressures. The effects of varying the backpressure on the rate of fluid production are discussed below under "Reservoir Engineering."

Preparations for Long-Term Flow Test Phase 2: From January 3 to January 25, a small 1.2 l/sec (19 gpm) pump was used to maintain enough flow through the system to prevent freezing. During this period arrangements were completed to lease a centrifugal injection pump, which was installed, tested and put into service on January 25. However, electrical and control problems arising from its relatively high electrical-power requirement led to another shutdown of the system on February 6.

The pump was returned to service on February 22 and the system was approaching equilibrium operating conditions when, on February 28, a major snow storm caused a power outage at the site. By then the system controls had been modified so that this automatically shut in the injection well and initiated bypass flow from the production well sufficient to prevent freezing of surface components. This continued until the power company restored electrical service to the site on March 1. Flow testing was then resumed.

During March, there were several short shutdowns of closed-loop fluid circulation, due to electrical problems in the control circuit of the power supply to the injection pump—which were finally corrected on March 29. Thereafter, pump operation was trouble-free. However, there was also one short shutdown in March because of a power outage to the site.

Long-Term Flow Test Phase 2: In spite of the shutdowns described above, during March the Phase II system produced thermal energy 85.4% of the time. However, as is illustrated in Table 1, operating conditions between shutdowns were consistent with each other. They were also similar to those maintained during the Phase 1 LTFT in 1992. Average water consumption for the entire month was 0.66 l/s (10.5 gpm) or—accounting for shut-in periods—10.4% of the total injected flow. From the standpoint of reasonably continuous operation and in the absence of systematically induced shutdowns, it seems reasonable to designate February 22 as the start of Phase 2 of the LTFT.

TABLE 1
HDR System Operating Data for March 1993

	March 7	March 14	March 22
INJECTION			
Pressure MPa	27.25	27.25	27.34
Flow Rate l/s	6.82	6.96	6.66
Temperature °C	29.1	22.1	26.1
PRODUCTION			
Pressure MPa	9.646	9.666	9.660
Flow Rate l/s	6.36	5.94	5.89
Temperature °C	182.5	181.5	183.1
Thermal Power MW (BTU/s)	4.08	3.96	3.87
Water Loss %	1.8	9.6	6.2

A flowing temperature survey of the production wellbore was made on March 16, 1993, when, as is shown in Table 2, operating conditions were essentially the same as those in effect at the time of a similar survey made on July 16, 1992, during the first phase of the LTFT.

TABLE 2
Production Conditions During Logging Runs

Date of Log	July 16, 1992	March 16, 1993
Surface Temperature °C	183.0	183.0
Backpressure, psi	1303	1401
Flow Rate, gpm	92.2	94.3

It is evident from Figure 12, below that down to the bottom of the casing at a depth of 3200 meters (10,500 ft), the two temperature logs were also nearly identical.

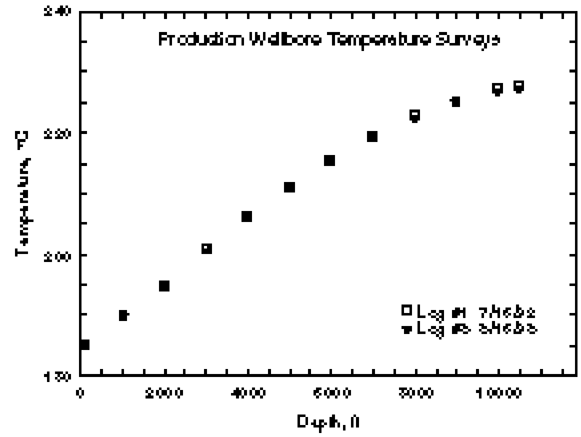


Figure 12. Production wellbore temperature surveys on two different dates. The data show essentially no changes in the production-fluid temperature profiles over an 8-month period.

However, in the fractured open-hole section below the casing—the fluid-production zone—there were significant differences. Figure 13 is a detailed temperature profile of that section from the log run on July 16, 1992.

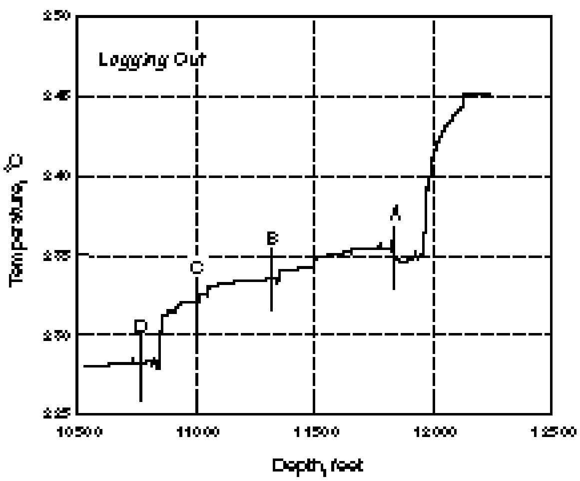


Figure 13. Temperature profile taken on July 16, 1992, across the fluid-producing interval of the production wellbore. The temperatures at points A, B, C, and D are compared in Table 3 to those found at the same points in a similar survey conducted on March 16, 1993.

In Table 3, temperatures at the depths indicated by the vertical bars labeled A, B, C, and D of Figure 13 are compared with the fluid temperatures measured at the same depths on March 16, 1993. The temperature differences are discussed later in this report under "Reservoir Engineering."

TABLE 3
Comparison of Fluid Temperatures During Logging Runs at Specific Points Across the Fluid Production Interval of the Production Wellbore

	7/16/92 Log	3/16/93 Log	Difference °C
Point A (11,840 ft)	234.5°C	231.5°C	-3.0
Point B (11,320 ft)	233.4°C	232.4°C	-1.0
Point C (10,990 ft)	232.0°C	231.5°C	-0.5
Point D (10,750 ft)	228.2°C	227.8°C	-0.4

Due to a funding shortfall, it was necessary to shut down the LTFT on April 17, 1993. Using the new centrifugal injection pump, the system had operated reliably since February 22 and it had been on-line and producing thermal energy 100% of the time since March 31. Average water consumption near the end of the period of continuous flow testing (April 1 to 17) was 0.46 l/s (7.4 gpm), or 7.1% of the injected volume.

Cyclic Operations: Observations made during earlier, unplanned shutdowns had indicated that, when the production well was shut in, the resulting redistribution of pressure in the fracture system led to a temporary reduction in overall system flow-impedance. To evaluate this phenomenon, the production well was intentionally shut in for 25 minutes each day during the period April 15-17. Results of this short experiment in cyclic reservoir operation confirmed that intermittent brief closures of the production well indeed enhanced the overall productivity of the reservoir.

To further evaluate cyclic operation of the reservoir, a short flow experiment was initiated on May 4. It called for continuous injection into the reservoir but with production for only 8 hours a day. On May 6, during the production period of the third such cycle, the production flow rate increased suddenly (in less than one minute) by almost 50%. The flow increase occurred with no coincident seismic activity and with an increase of about 6°C (11°F) in the temperature of the produced fluid. To assess this phenomenon, the system was immediately brought into continuous production, which continued until May 17 when the lease extension on the injection pump expired. The system was then shut in and the pressure in the reservoir was allowed to decay. By the end of May, it had declined to 19 MPa (2750 psi).

Standby Operations: Beginning in early June, the surface system was put on standby status. Various components such as piping, valves, and the heat-exchange were drained and refilled with antifreeze or appropriate lubricating fluids, to prevent deterioration from non-use.

There was no fluid injection into the Phase II Fenton Hill reservoir during the rest of Fiscal Year 1993. As a result of diffusional losses to the rock surrounding the reservoir and the long-standing leak up the annulus around the injection well tubing, pressure in the reservoir declined steadily.

During June, the average rate of fluid loss up the injection wellbore annulus was approximately 0.40 l/s (6.3 gpm). By the end of the month reservoir pressure had dropped to about 15 MPa (2200 psi). At the end of July, reservoir pressure had decreased to about 12.3 MPa (1780 psi) and the leak in the injection well annulus had decreased slightly, averaging about 0.39 l/s (6.2 gpm). The reservoir pressure had dropped to about 10.5 MPa (1520 psi) by the end of August, while the bypass flow up the annulus averaged 0.36 l/s (5.8 gpm). Finally, during September, the reservoir pressure decreased to about 8.8 MPa (1275 psi) and leakage flow from the injection-well annulus averaged 0.36 l/s (5.8 gpm).

It had previously been determined by geochemical analysis that the leak up the annulus of the injection well resulted from a connection to the fractured reservoir at a location above the cemented-in section of the casing. With the circulation loop shut in, continuous cooling of the annulus by water flowing down the injection tubing no longer occurred, and less heat was therefore removed from the hot water flowing up the annulus from the reservoir. As a result, the water reaching the surface through the annulus had warmed to 50.6°C (123°F) by August 16.

The Injection-Pump Problem: Flow testing of the Fenton Hill Phase II HDR system depends, among other things, on reliable operation of a high-pressure, high-volume pump to inject water into the fractured subterranean reservoir. As was discussed in the Fiscal Year 1992 Progress Report of the Los Alamos National Laboratory HDR Program, two plunger-type 5-cylinder Ingersol-Rand (IR) injection pumps had been procured especially for the long-term flow test (LTFT) of the Phase II system at Fenton Hill. Unfortunately, both of these pumps failed within hours of each other in late July 1992, as evidenced by water leakage through hairline cracks in their cylinder blocks. This forced an unplanned suspension of the LTFT.

Following a 3-week reservoir shut-in, the decision was made to continue flow testing the Phase II reservoir at an injection pressure of 22.3 MPa (3240 psi), a level about 20% lower than that applied during the LTFT, until a replacement pump with injection capabilities equivalent to the IR pumps could be located, procured, and installed. An old backup pump that had been used for a number of years for short-duration testing at Fenton Hill was plumbed into the circulation loop and used on a continuous basis until it died of “old age” with a cracked cylinder head, in early October 1992. This phase of testing, at a reduced injection rate of about 4.4 l/s (69 gpm), is now referred to as the Interim Flow Test (IFT). Although LTFT-quality results were not obtained, this period of steady-state reservoir flow testing did provide a very significant off-design operating point for subsequent HDR reservoir model verifications.

Following an additional 4-week reservoir shut-in while an oil-field-type, high-pressure, high-capacity piston pump was leased and installed, flow testing was begun again on October 29, 1992. However, this pump (referred to in the industry as a mud pump) was designed to circulate drilling fluids containing additives with some degree of lubricity. It suffered repeated failures (particularly during the month of November), mainly because of erosion of the rubber piston seals from pumping the very clean water at Fenton Hill. A redesign of the pistons and seals afforded a somewhat improved pump longevity, and testing continued through December with fewer interruptions. During the period from December 4, 1992, to January 3, 1993, we were able to obtain two additional off-design steady-state reservoir operating points at elevated production backpressures of 12.4 and 15.2 MPa (1800 and 2200 psi).

Early in the fall of 1992, because of the repeated problems with piston-type pumps, we had begun to investigate the possibility of employing a multistage centrifugal pump for our operations at Fenton Hill. The operating capacity with this type pump had been improved markedly in the several years since the order for the IR pumps had been placed, and one manufacturer, REDA of Bartlesville, OK, had recently supplied several pumps with specifications close to those needed at Fenton Hill for oil field water-flooding operations in western Canada. Therefore, an order was placed in December 1992 to lease a REDA pump manufactured specifically to meet the LTFT injection requirements. The rental mud pump suffered a “terminal” failure on January 3 (near the end of its 3-month lease), only about 2 weeks before the scheduled delivery of the REDA pump to Fenton Hill. The REDA pump was installed by January 25, then tested and brought on line by February 3.

The REDA centrifugal pump, unlike the piston pumps previously used during the LTFT, was powered electrically rather than by diesel fuel. It lacked the flexibility of the piston pumps and was somewhat more expensive to run, but it was simpler to operate and maintain. Unfortunately, the power requirements of the new pump pushed the electrical power capacity of the Fenton Hill site to its limit, and in early February 1993 larger underground cables had to be pulled to the substation supplying power to the pump.

With the installation of the new cables and other auxiliary electrical components to handle the increased power load and special control requirements of the REDA pump, reservoir injection was initiated on February 17. Two separate but brief interruptions of the electrical power supply to the site occurred during the February 20-21 weekend, but in each case the injection pump was restarted automatically with no perceptible interruption of fluid supply to the system.

During March, there were several short shutdowns due to problems in the electrical supply to the pump. These were solved and corrected when, on March 29, a service technician from the pump manufacturer identified and replaced a defective capacitor in the circuit control for the pump motor. Thereafter the injection pump operated reliably and without interruption until the system was shut down on April 14 for lack of operating funds. However, an arrangement with the manufacturer permitted the pump to be kept in place and operated intermittently in short-term experiments until May 17, when it was removed from the system and shipped back to the manufacturer. Aside from the electrical-supply problems involved in bringing it into continuous operation, the centrifugal pump performed very satisfactorily in satisfying the injection requirements of the LTFT.

Reservoir Engineering

As described above, operation of the Fenton Hill Test Facility during Fiscal Year 1993 was disappointing with regard to continuation of the LTFT. Between initial difficulties in identifying, procuring, and installing a suitable injection pump and a later funding shortfall, only 55 days of continuous, LTFT-quality circulation was achieved. It is significant, however, that the operational difficulties were confined entirely to failures of surface components and interruptions in the electrical-power supply to the Fenton Hill site. The subterranean heat-extraction loop, which is the essential part of an HDR energy system, was problem-free, and demonstrated an important capability to undergo repeated shutdowns and restarts without damage or significant changes in its operating characteristics. In addition, the results of Phase 2 LTFT testing virtually duplicated those of Phase 1 conducted nearly a year earlier, thus demonstrating the temporal stability of the Fenton Hill HDR system

In spite of the interruptions in the course of the LTFT, much was learned about the underground system during the year from observations during limited-term flow tests, logs and other measurements, and a number of special experiments. Significant new reservoir engineering information obtained during Fiscal Year 1993 is discussed below.

Effects of Backpressure Imposed at the Production Wellbore: During two brief flow-testing intervals in December 1993, equilibrium LTFT operating conditions were established at an injection pressure of approximately 27.3 MPa (3960 psi) but with two different backpressures maintained on the production wellhead. Equilibrium conditions had also been established during an April-July 1992 LTFT run segment at a similar injection pressure but with a still different backpressure. Production flow rates under these three backpressure conditions are plotted in Figure 14.

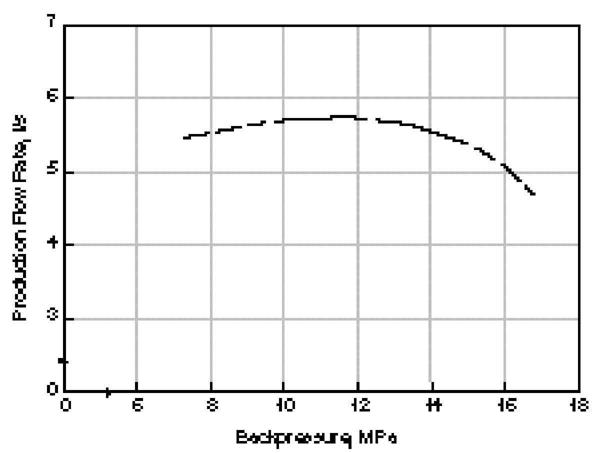


Figure 14.

Figure 14. The production flow rate from the Fenton Hill HDR reservoir changes only slightly as the backpressure on the production wellbore is varied from 9.7 to 15.2 MPa (1400 to 2200 psi).

Although only three data points have been obtained, they appear to show that, at a constant injection pressure of 27.3 MPa (3960 psi), there is a broad maximum in the production flow rate at backpressures between 9.7 and 15.2 MPa (1400 and 2200 psi). At a constant injection pressure, the reduction in pressure difference across the reservoir resulting from an increase in backpressure in the production well would normally be expected to reduce the production flow rate. At the same time, however, increased backpressure on the production wellhead would be translated to increased pressure, and consequently increased fracture opening, in that portion of the HDR reservoir located near the production wellbore. Evidently, in the Fenton Hill HDR system, these two factors tend to offset each other over an imposed backpressure range of 9.7 to 15.2 MPa.

This result is important, because the only energy that must be expended in operating an HDR system is the net energy required to overcome the impedance to flow. Although very high injection pressures may be required to open reservoir joints, it may be possible to recover a substantial portion of the energy imparted to the fluid during injection by imposing a high backpressure on the production well. The excess mechanical energy content of the fluid returning to the surface could then be recovered by pressure recuperation or alternatively the entire surface system could be kept at high pressure to reduce the net energy input required for injection in the recirculating mode. In either case, the energy efficiency of the system would be significantly improved.

Observed Changes in Flow Distribution: The temperature logs described earlier in this report under "Reservoir Operations," above, showed that over an eight-month period the fluid entering the wellbore at a depth of 3,609 m (11,840 ft) had cooled by 3.0°C (5.4°F). However, at a depth of 3,276 m (10,750 ft)—just above the highest and coolest fracture connection—the fluid had cooled by only 0.4°C (0.7°F) and there was no significant difference in the temperature of the fluid entering the cased section of the wellbore at 3,200 m (10,500 ft). This suggests that there had been a slow change in flow distribution through the reservoir, with the decrease in flow rate through the deepest flow path (which had cooled the most) being compensated for by an increase in flow rate through the intermediate-depth flow paths. Based on these observations, it appears that, as they cool, fractures in HDR reservoirs may actually carry proportionately less of the total flow. In other words, HDR reservoirs may be self-perpetuating, with cooled flow paths automatically shutting down over time.

Determination of Reservoir Impedance Distribution: When Phase 1 of the LTFT was suspended on July 31, 1992, both wellheads were shut in quickly and simultaneously. The pressure response at each wellhead is plotted in Figure 15.

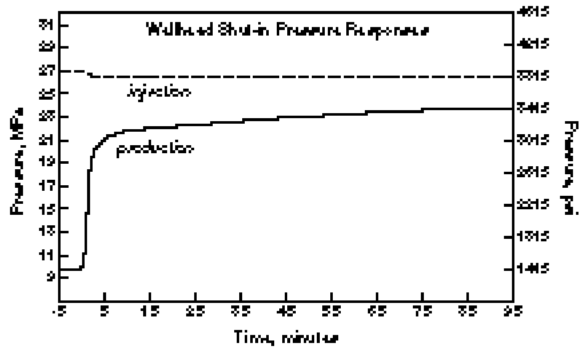


Figure 15. The disproportionately large increase in pressure measured at the production wellhead upon shut in of the HDR system at Fenton Hill indicates that the majority of resistance to flow through the reservoir is concentrated in the vicinity of the production wellbore.

Pressure measurements showed a step decrease of about 0.7 MPa (100 psi) at the injection well (primarily because the frictional resistance was essentially reduced to zero) followed by a slow pressure decline toward the mean reservoir pressure. At the same time, the pressure at the production wellhead rose rapidly by about 12 MPa (1700 psi) and then increased slowly toward the mean reservoir pressure. These data indicate that the pressure gradient across the reservoir levels out rapidly near the production wellbore where it is steep, and slowly across the body of the reservoir where it is moderate.

Using this data, the overall flow impedance of the reservoir can be divided into three components: an inlet impedance, a body impedance, and an outlet impedance. The small but steep pressure drop at the injection wellhead quantifies a relatively small inlet impedance due largely to frictional resistance to flow down the wellbore. The reservoir-inlet flow connections are thermally dilated as well as pressure-propped. The large pressure rise in the production well indicates a large pressure gradient near the reservoir outlet to that well. The region near the production wellbore is the least pressurized part of the reservoir during normal operation. Joints in that region, therefore, are least open and show the largest resistance to flow. Finally, the residual pressure difference between the two wells after the initial rapid changes represents the moderate pressure drop across the body of the reservoir.

These measurements reflect actual LTFT operating conditions. They show that the most effective way to improve the performance of the Phase II system would be to reduce the impedance in the region of the reservoir near the production wellbore. Techniques to do so are being developed. The data also indicate that, because the bulk of the reservoir impedance is concentrated in the vicinity of the production wellbore, it may be possible to create larger and more productive HDR reservoirs by spacing injection and production wellbores farther apart, without simultaneously engendering large increases in the overall system impedance.

Observed Abrupt Drop in Reservoir Impedance: As mentioned above, a sudden drop in the impedance of the reservoir occurred on May 6, 1993. It was manifested in the form of an increase in the rate of production flow by nearly 50% from 9.84 l/s (156 gpm) (a level which was already anomalously high because production had just been restarted after a scheduled production-well shut in) to 14.5 l/s (231 gpm) within a period of less than a minute. The increased flow was accompanied by an apparent increase in the reservoir fluid temperature as reflected in a larger rise in the temperature of the fluid produced at the surface at the higher flow rate than would be expected on the basis of flow rate considerations alone.

After the sudden large drop in reservoir impedance, the system was brought into steady-state production in order to allow comparison of the new flow conditions with those observed during the last part of Phase 2 of the LTFT a few weeks earlier. In the face of the lower-impedance reservoir characteristics, however, the capacity of the REDA centrifugal injection pump was found to be insufficient to maintain the injection pressure of 27.3 MPa (3965 psi) at which the Phase 2 LTFT segment had been run. While the production backpressure could be maintained at 9.7 MPa (1400 psi), the maximum injection pressure level that could be achieved was only 26.5 MPa (3850 psi), a drop of 0.8 MPa (115 psi) from the earlier LTFT injection pressure.

During the following 10 days of continuous production at the standard LTFT conditions (except for the slightly lower injection pressure), the flow rate remained more than 40% higher than that prevailing during the Phase 2 LTFT a few weeks earlier. Table 4 compares operating parameters averaged over a 7-day period ending on May 17 to those from the last 7 days of Phase 2 LTFT testing in April 1993.

The data in Table 4 show a 42% reduction in impedance during the May 1993 flow test period compared to that prevailing about a month earlier in spite of the lower net pressure driving the fluid across the reservoir. Had it been possible to maintain the driving pressure at the higher LTFT level, an even larger drop in impedance would, no doubt, have been observed. The negative water loss rate seen during May 10–17, is a function of the reduction in the pressure imposed on the reservoir and the consequent inflow of water stored in the far field. It has no long-term operational significance.

TABLE 4
Comparative HDR System Operating Data

Injection	**Final LTFT Week (April 10-17)**	**After Impedance Drop (May 10-17)**
Pressure	27.34 MPa	26.54 MPa
Flow Rate	6.50 liters/s	8.16 liters/s
Temperature	22.2°C	22.3°C
Production		
Pressure	9.71 MPa	9.74 MPa
Flow Rate	5.73 liters/s	7.82 liters/s
Temperature	183.9°C	190.3°C
Bypass Flow Rate	0.347 liters/s	0.374 liters/s
Derived Parameters		
Impedance	3.08 MPa/(l/s)	2.15 MPa/(l/s)
Water Loss Rate	0.426 l/s	-0.025 l/s
Thermal Power	3.88 MW	5.50 MW

In order to further investigate the observed change in reservoir productivity, a Kuster temperature log of the production well was carried out on May 11. The log measured the produced-fluid temperature to the bottom of the cased portion of the production well (but not, unfortunately, into the productive, open-hole zone of the wellbore). As illustrated in Figure 16, the mixed-mean temperature of the water being produced from the reservoir in May 1993 was essentially the same at the top of the reservoir production zone (about 3,185 m or 10,450 ft) as that observed in earlier Kuster logs. Thus, the newly produced fluid must, on average, originate from reservoir zones of about the same temperature as those which have been productive throughout the LTFT.

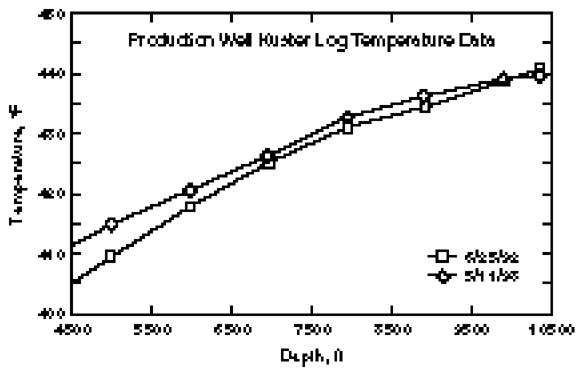


Figure 16. Kuster logs of the Fenton Hill production well show that the temperature of the produced fluid was essentially the same in May 1993 as it had been in June 1992. The surface temperature of the fluid was higher in 1993 because the greater flow rate at that time resulted in less heat loss to the surroundings as the fluid traveled up the wellbore.

A tracer test was subsequently run on May 15-17. Figure 17 is a graph of that tracer data as well as the results from two previous tracer experiments.

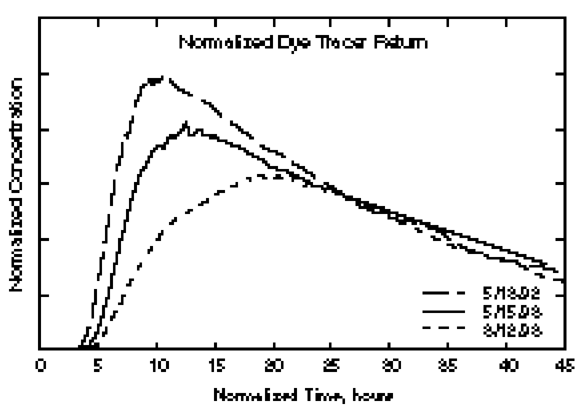


Figure 17. Tracer return profiles from three tracer experiments. The tracer return time in May 1993 was intermediate between that of March 1993 and that of May 1992.

The shortened first appearance time of the May 1993 tracer indicates development of one or more shorter pathways through the reservoir between March and May 1993. It is probable that the development of the shorter flowpath(s) was associated with the rapid impedance drop observed on May 6. It is noteworthy that the shortest transit time through the reservoir in the May 1993 tracer test was still somewhat longer than the shortest transit time observed in May 1992, a few weeks after the start of Phase 1 of the LTFT.

The rapid decline in the system impedance on May 6, 1993, is by far the most significant change observed in HDR reservoir behavior in over 20 years of research and development experience at Fenton Hill. Since previous logs had shown that at least 7 primary joints were discharging fluid from the reservoir into the production wellbore, it is possible that the sudden large increase in flow was due to the opening of more than one additional new joint. A wireline log of the production wellbore could be employed to obtain information about the number, location, and flow characteristics of new joints arising from the event of May 6, 1993. Unfortunately, budget limitations precluded conducting such a log at that time, and the system would have to be restarted and stabilized to carry it out in the future.

Studies of Cyclic Reservoir Operations: Operation of HDR systems on a cyclic basis, wherein the production and/or injection wells are purposely shut in periodically, may have both production and marketing advantages. For example, a cyclic production schedule could be employed to supply energy from an HDR reservoir for a limited time period in larger amounts than could be produced continuously from the same resource. This mode of operation might be especially apropos for meeting peak-power needs of electric utilities.

Until recently, all experimental data in regard to cyclic performance of HDR reservoirs was obtained from short unintentional system shut-ins during experiments being conducted primarily for other purposes. Near the close of the long-term flow testing effort in April 1993, however, two brief experiments were conducted expressly to evaluate cyclic production from the Fenton Hill HDR reservoir.

In the first test on April 15–17, 1993, injection was maintained at a steady rate, but the production well was shut in for 25 minutes, once in every 24-hour period. Figure 18 shows the injection and production wellhead pressures and the production flow profile for the week of this three-day test.

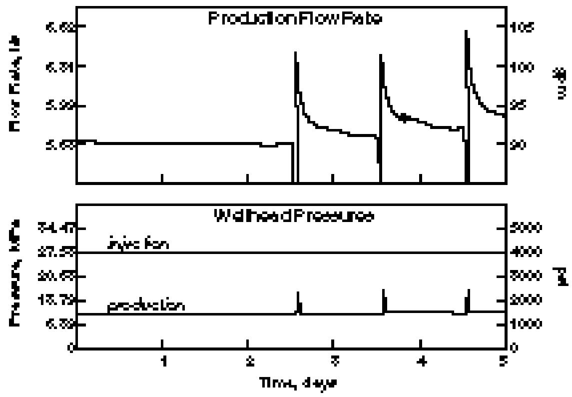


Figure 18. Injection and production pressures and production flow rates during cyclic flow testing of the Fenton Hill HDR reservoir.

On each test day, the pressure at the production wellhead rose sharply when it was shut in. When production was resumed, the initial flow rate was greatly elevated. While the flow rapidly tapered off toward more normal levels, it never quite returned to the lowest level of the previous day. Figure 19 is a histogram showing the daily power production for the three days of this cyclic experiment as well as the two days just preceding it.

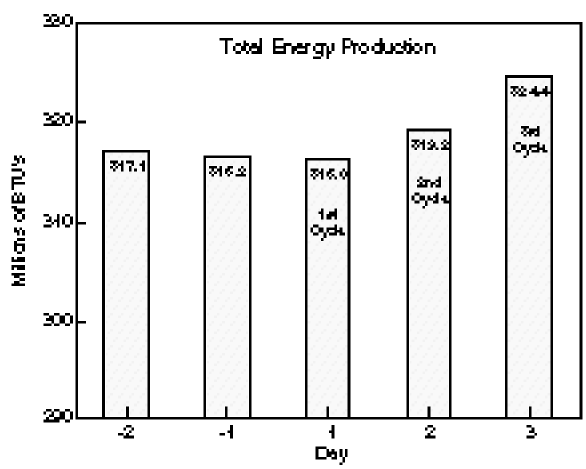


Figure 19. Energy production prior to and during cyclic flow testing of the Fenton Hill HDR reservoir. Cyclic operation of the reservir reversed a slow downward trend in energy production.

The data of Figures 18 and 19 demonstrate that the slow downward trend in production typically observed during steady-state operation of the Fenton Hill reservoir can be reversed by briefly shutting in the production well once a day. This short cyclic experiment was terminated after three days when the computer control system at Fenton Hill responded to an off-normal alarm by automatically shutting down the circulation system at a time when operating personnel were not on site. Nonetheless, even this limited test provided a significant indication that production-well cycling can have a marked positive effect on the operation of an HDR system.

A second cyclic test was undertaken on May 4. It entailed continuous injection, but production on a schedule involving 8 hours of flow followed by 16 hours of production-well shut in. On the morning of May 6, 1993, about an hour after the production well had been reopened as part of the third cycle, a sudden, large drop in reservoir impedance occurred. In order to investigate the ramifications of the impedance change under the most straightforward operating conditions possible, the cyclic experiment was terminated and the system was brought to continuous circulation.

As discussed above, the impedance drop observed during this second cyclic test was the most significant change in reservoir behavior observed in over 20 years of experience at Fenton Hill. In fact, with this cyclic experiment, a very practical technique for increasing HDR reservoir productivity may have been discovered. If so, there is a very real potential for dramatically lowering the cost of energy from HDR. It is impossible, however, to draw any definitive conclusions regarding the cause of the increased flow without well-designed tests to verify the initial findings. In summary, these two brief experiments provided dramatic evidence of the potential of cyclic operational schemes to significantly improve the performance of HDR reservoirs.

Joint Closure Upon Reservoir Pressure Decline: After the termination of testing at Fenton Hill on May 18, 1993, the reservoir pressure was allowed to decay naturally for the balance of Fiscal Year 1993. Over a span of 135 days to the end of September, the pressure fell from about 23.4 MPa (3400 psi) to 8.62 MPa (1250 psi). This pressure decline reflects a decrease in the volume of water stored in the reservoir due to water losses resulting from diffusion into lower-pressure regions beyond the fractured rock body and escape through the leakage path back to the surface via the annulus of the injection wellbore. Since both these water-loss mechanisms are themselves pressure-dependent, the rate of pressure decline decreased with time as illustrated in Figure 20.

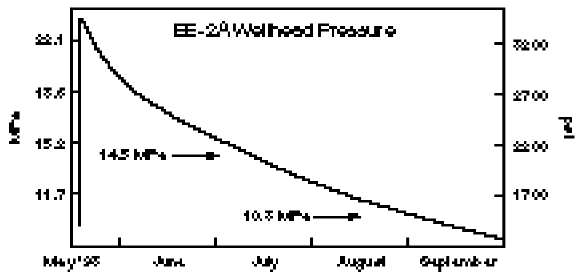


Figure 20. Wellhead pressure versus time during a period when the Fenton Hill HDR reservoir was shut in. Inflection points in the pressure decline curve were observed at about 14.5 MPa (2100 psi) and 10.3 MPa (1500 psi).

In addition, because the aperture sizes of the reservoir joints are dependent upon both the imposed pressure and their orientations with respect to the in situ stresses, the decreasing water storage capacity of the gradually closing reservoir joint sets also influences the pressure decline observed at the surface. The activity of joint sets within the reservoir is thought to be responsible for the inflection points found at about 14.5 MPa (2100 psi) and 10.3 MPa (1500 psi) in the curve of Figure 20. Figures 21a and 21b show the pressure decline in the regions of the two inflection points in more detail.

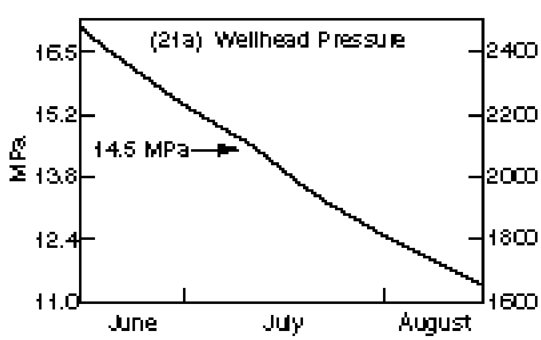
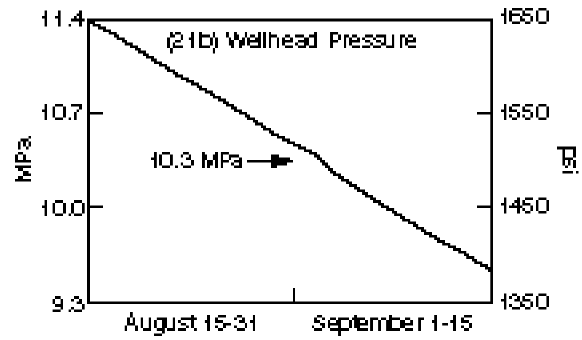


Figure 21a.



Figures 21a and 21b. Inflection points in the pressure decline curve of the Fenton Hill HDR reservoir are more obvious when shown on an expanded scale.

The inflection points (both of which show a temporary trend toward a faster rate of pressure decline) indicate that a set of joints has reached its closure stress. At pressures below this point, joints from that set can no longer supply nearly as much water to the diffusion and leakage water-loss pathways. Since the reservoir outflow pathways are then supplied from a decreased volume, the pressure of the reservoir declines at a slightly faster rate. An increase in the annulus flow was observed coincident with the 14.5 MPa inflection point so the inflection is at least partly due to an increase in this annulus flow. That pressure is also likely to correspond to the closure pressure of one joint set within the reservoir, however.

When the hydrostatic pressure of the column of water in the wellbore is added to the inflection-point pressure observed at the wellhead, a measure of the effective closure stress of a particular joint set is obtained. Likewise, a joint set will open at any imposed pressure level above its closure stress. Along with major joint sets with closure stresses on the order of 22.0 MPa (3200 psi) or higher, the evidence obtained over the last several months of Fiscal Year 1993 indicates that the Fenton Hill HDR reservoir contains two significant joint sets which open at applied surface pressures of 10.3 MPa and 14.5 MPa, respectively.

Geochemistry

Analyses of the Produced Fluid: As has been described above, a sudden drop in the impedance of the HDR reservoir was observed during a cyclic-flow experiment on May 6, 1993. That event was reflected in a 48% increase in the production flow from the reservoir within a period of less than a minute and with a significant increase in the fluid production temperature. The impedance drop has been attributed to the sudden opening of new joints intersecting the production wellbore. It could be anticipated that new pathways through the reservoir carrying a significant portion of the fluid might affect the geochemical composition of the water. However, as summarized in Table 5, results of geochemical analyses before and after the impedance event show no significant differences in the composition and or concentration of dissolved solids. They also are closely similar to production-fluid analyses made during the Phase 1 LTFT segment of April-July 1992.

TABLE 5
Dissolved solids in HDR production fluid, after and prior to impedance reduction event of May 6, 1993 (parts per million by weight)

	Concentration in Production Fluid (parts per million by weight)	
Species:	May 7, 1993	March 5, 1993
Chloride	890	1002
Sodium	839	899
Bicarbonate	469	556
Silicate (as S_iO_2)	419	402
Sulfate	328	342
Potassium	90	91
Boron	30	34
Calcium	13	17
Lithium	15	15
Fluoride	15	13
Bromide	4.6	5.1
Arsenic	3.0	3.5
Iron	0.3	0.3
Aluminum	0.8	0.8
Ammonium	1.0	1.3
Strontium	0.6	0.8
Barium	0.1	0.2
Total Dissolved Solids	3118	3387

Suspended solids levels of 88 ppm were measured in the circulating fluid on May 7, 1993, shortly after the abrupt impedance drop. During the previous two months, suspended solids analyses had been conducted on 15 separate occasions with measured levels ranging from less than 1 ppm up to 130 ppm. The pH of the pressurized fluid on May 7, one day after the impedance drop, was 5.27. Prior to that event on May 5, it was measured at 5.35. The pH values of depressurized samples (from which some of the dissolved carbon dioxide would have escaped) measured at the same times were 6.00 and 5.93, respectively.

In summary, essentially no effect on the geochemistry of the produced water was observed as a result of the abrupt drop in reservoir impedance. The geochemical constitution of water recirculated through the Fenton Hill HDR system had previously been found to rapidly stabilize at a low and essentially constant level of dissolved solids and gases. These results further highlight the geochemical stability of the circulating water at Fenton Hill.

Geochemistry Data Relevant to HDR Plant Hardware: Three plant operations problems that might be expected in the operation of an HDR energy plant are scaling, corrosion, and the evolution of gases from the circulating fluid. These are addressed below with respect to actual experience and the implications that can be drawn from the geochemical data collected during flow testing over the past year.

Scaling: To date, no scaling has been detected in any of the surface plant piping or equipment. Silica scaling was anticipated to the only type of depoisition that mihgt be a problem but, in fact, no silica scale has been observed. The Fenton Hill production fluid is saturated with respect to quartz at 230-240°C, but it appears that the solution becomes supersaturated when cooled in the heat exchanger without deposition of either quartz or amorphous silica.

It is important to note that the Fenton Hill Plant, as a prototype of a typical HDR facility, operates as a pressurized closed loop in which the circulating fluid is kept at a high enough pressure in all parts of the system so that no flashing to steam takes place. Steam generation, of course, could result in a large increase in the concentration of solids in the liquid phase and greatly increase the probability of scale formation. Further, liberation of carbon dioxide is known to cause calcite deposition in geothermal surface plants, but pressurized closed-loop operation will retain the carbon dioxide in the circulating fluid and also prevent this form of scaling.

Corrosion: Corrosion rates have not been specifically monitored during the flow-test program at Fenton Hill, but visual observations have not indicated any significant corrosion effects. In comparison to many conventional hydrothermal fluids, the water being continually recirculated through the Fenton Hill HDR reservoir has been found to quickly reach a relatively low and constant level of dissolved solids (3,000-4,000 ppm), and be only mildly acidic (pH 5-5.6). Suspended particulates are essentially absent. On the basis of hundreds of geochemical analyses over the past year, it thus appears that, in this particular system, corrosion of surface plant components will not be a problem.

Dissolved Gases: There were virtually no emissions of gases to the atmosphere during closed-loop long-term testing at Fenton Hill. Like the dissolved solids, dissolved gases in the circulating fluid rapidly reached a constant level (about 3,000 ppm). At the gas concentrations and the temperatures prevailing in the hot portion of the production side of the surface plant, which includes a gas separator, the total vapor pressure of the hot fluid (water vapor pressure plus the partial pressures of the dissolved gases) reached only about 2.1 MPa (300 psi).

Since operating pressures of 3.4 MPa (500 psi) or greater were maintained in this part of the loop, no gases were emitted to the atmosphere. As a result, the gas separator, although on-line, did not separate any gas. Carbon dioxide was found to be by far the predominant gas in the circulating fluid, constituting well over 95% of the total dissolved gases. Hydrogen sulfide was generally detected at levels of less than a part per million, which is well below the concentration found in many natural geothermal fluids.

Tracer Studies: In an experiment conducted in September 1992, relatively clean water was injected into the Fenton Hill HDR reservoir over a period of several days to replace the water that had been recirculating for several months. This operation was in effect a tracer test involving naturally occurring ions such as sodium and chloride, dissolved silica, and a host of other compounds. The tracer injection in this experiment is known as a washout test, since it constitutes a negative step change in the concentration of the tracer species.

Results of the washout test indicated that none of the dissolved species behaved as truly conservative tracers. Many species such as chloride ion, for example, exhibited breakthrough curves that implied a source within the reservoir, either through active dissolution from the rock matrix or, more probably, from rock pore fluid which contained a relatively high concentration of the component.

Other species, such as dissolved silica, indicated that rock-water interactions including dissolution, precipitation, absorption and adsorption were occurring within the reservoir on a time scale of several days. The washout experiment thus provided additional information about the rock-water interactions that give rise to the overall geochemical content of the circulating fluid in the Fenton Hill HDR system. In addition, the results of the fresh water flush strengthened the conclusion reached in earlier tracer experiments that a small but significant fraction of the production fluid comes from water that spent a long time percolating through a large region of rock.

A conventional tracer test (in which a nonreacting dye is added to the recirculated fluid) was conducted beginning on April 12, 1993, to evaluate the reservoir under steady-state flow conditions and provide a basis for comparison with tracer data from earlier tests when the system was being operated under similar conditions. Figure 22 illustrates fluorescein dye tracer recovery for this tracer test as well as for tests conducted during May and July 1992. The figure makes it clear that the trends toward longer first-arrival and peak-response times, originally noted during Phase 1 of the LTFT continued through the Phase 2 test period.

These data provide evidence of profound changes in the fluid flow patterns within the reservoir, probably due to heat extraction as production proceeded. As heat was extracted, the fluid was redistributed toward more circuitous fracture paths, resulting in a more efficient sweep of fluid through a larger region of hot rock.

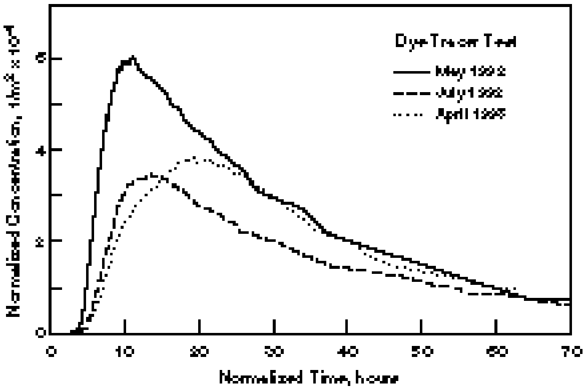


Figure 22. Recovery of fluorescein dye tracer on three occasions during the LTFT. As flow testing proceeded, the initial appearance of the tracer and the peak recovery point shifted to longer and longer times, indicating that the fluid was following longer paths through the reservoir.

Fluorescein dye undergoes some degradation in passing through a hot geothermal reservoir. During flow testing at Fenton Hill, the extent of this effect appeared to vary from test to test in an unpredictable manner. As a result, the total recovery of the dye tracer (measured by the areas under the recovery curves) was not predictable. In all three of the tracer tests referred to above, a nonreactive organic tracer was run at the same time as the fluorescein dye. The organic tracer data supported the general trends indicated by the fluorescein results and provided a more quantitative picture of flow redistribution.

As discussed above under “Reservoir Engineering,” another dye-tracer test was run in May 1993 to investigate the changes in reservoir geometry that may have led to the sudden, large, reduction in flow impedance through the reservoir observed at that time. On the basis of a significant shift in the peak-recovery point toward a shorter time, it was concluded that the impedance reduction resulted from the opening of one or more new, relatively short, flow paths through the reservoir.

Seismology

A microearthquake originating in the Fenton Hill HDR reservoir occurred at 12:03 am on December 24, 1992. It was near the lower limit of microearthquake detectability but was recorded on all three seismometers in the Precambrian seismic network. This was the first microseismic event observed at Fenton Hill in several years of pressurization and flow testing. Its source location could not be determined accurately, but was at a depth of approximately 3200 meters (10,500 ft) and about 300 meters (1,000 ft) north of any microearthquake previously observed there. A spontaneous change in flow rate through the reservoir occurred 34 minutes later, although a definite relationship of this event to the microearthquake has not been established.

Nine days later, at 4:51 pm on January 2, 1993, a second microearthquake was detected. It was even smaller than the first one, but was similar in character. Again, its source location could not be determined accurately, but was at a depth of approximately 3650 meters (12,000 ft) and about 900 meters (3000 ft) south-southwest of the first event—in a region of the fractured reservoir where microseismicity had previously been observed. At the time of this event the system was operating at a steady flow rate, and no changes in operating parameters were observed that could be related to it.

During the next several months, 47 additional microseismic events were recorded. It was possible to reliably determine the locations of 31 of them. These were all found to be located at a shallower depth and further to the north than the large number of seismic events associated with the massive hydraulic fracturing experiment of 1984 during which the reservoir was originally created. However, the locations of the recent events correlated closely to seismicity observed at shut-in periods during the initial 30 day flow test of the reservoir in 1986. The seismic events of 1986 were considered possibly due “to increased pressures in the production side of the reservoir after shut-in” (ICFT: An Initial Closed-Loop Flow Test of the Fenton Hill Phase II Reservoir, Los Alamos Report LA-11498-HDR). The LTFT was designed to be operated at injection pressures just below the anticipated threshold of seismic stimulation.

After several short preliminary flow periods during December 1991 and the early part of 1992, a continuous flow test of 112 days’ duration was begun on April 8, 1992. This was followed by about 6 months of intermittent flow operation and then another continuous run lasting from the beginning of March to mid-April 1993. After an additional short flow test period from late April to mid-May 1993, the wellheads were shut in and the reservoir pressure was allowed to decay as the Fenton Hill HDR site was put on standby status. Figure 23 shows the injection and production well pressures from April 1992 through the close of the flow test period in May 1993.

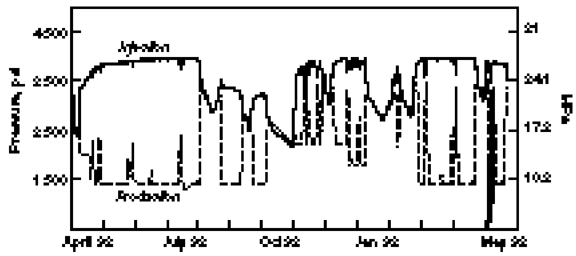


Figure 23. Injection and production well pressures during the entire period of flow testing from April 1992 through May 1993. Pressures were always kept below 27.6 MPa (4,000 psi), which experience had shown to be the threshold pressure for the onset of seismicity and reservoir expansion.

The figure makes it clear that injection wellhead pressures were consistently held at a level somewhat below 27.6 MPa (4,000 psi). Pressures at the production wellhead were typically maintained at 9.7 MPa (1400 psi) during flow periods. During shut-in periods, the injection and production wellhead pressures tended toward an intermediate equilibrium value.

Figure 24 relates the occurrence of seismicity to the wellhead pressures during the period December 1992 through May 1993. It appears that, in general, seismic events occurred at times of high production wellhead pressures. These in turn indicate those periods when the system was shut in for one reason or another and the reservoir (in the absence of an imposed pressure gradient between the injection and production wellbores) was equilibrating to a uniform pressure throughout.

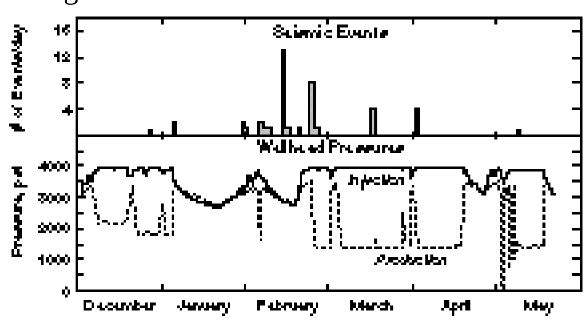


Figure 24. Wellhead pressures (lower graph) and seismicity (upper graph) during the period December 1992 through May 1993. No seismic events were observed during 8 months of flow testing prior to December 24, 1992.

It is interesting to note that the reservoir underwent a sudden large drop in impedance in early May 1993, with no accompanying indication of significant seismic activity. The long aseismic period of flow testing, the relatively small number and low rate of occurrence of the seismic events subsequently observed, and the lack of a strong and consistent correlation of those seismic events to imposed conditions imply that the observed seismicity is related to some long-term relaxation of stresses within the reservoir, or perhaps more likely near its boundaries, arising from an extended period of flow operations. At present, the HDR Program does not have the resources needed to thoroughly evaluate the seismic information generated during the 1992-1993 flow testing effort.

Reservoir Modeling

For several years, an implicitly coupled model of rock deformation, fluid flow, and heat transfer has been development for use in simulating the Hot Dry Rock (HDR) geothermal reservoir at Fenton Hill, New Mexico. The goal of the model (GEOCRACK) is to provide engineers with a tool to address such questions as the number and spacing of wells for optimal heat mining, the effects of low impedance flow paths (short-circuiting), the effects of operating the reservoir in different modes (steady state or periodic pressurization), and the long-term thermal performance of the reservoir.

Because rock suitable for the development of HDR reservoirs is relatively impermeable, flow is concentrated in the joints, with the flow rate being a function of the joint openings and those joint openings in turn being a function of the fluid pressure and rock deformation. This coupling is incorporated in the model by discretely modeling the joints and rock blocks using the finite element method.

The fluid and structural models are nonlinear and tightly coupled (especially for transient calculations where fluid can be stored in the joints), making it necessary to formulate the model such that both the pressures and the displacements are solved simultaneously. The result of this formulation is that coupling terms are introduced between the fluid and structure models which speed convergence of the problem. Newton-Raphson iteration is performed until the nonlinear equations converge.

In Fiscal Year 1993, simulations of the Fenton Hill reservoir showed that the model correlates observed flow rates under different pressure conditions, replicates reservoir tracer behavior and reproduces the transient reservoir behavior observed at Fenton Hill. Figure 25 shows a typical mesh generated by GEOCRACK with discrete flow paths used to model the reservoir. Figure 26 compares predicted and measured pressure transients which occur as the reservoir is shut in, and Figure 27 shows a comparison of measured results of tracer tests on three occasions compared to the tracer response predicted by GEOCRACK. During 1994 heat transfer calculations will be coupled to the model so that it may be used to predict the thermal performance of the Fenton Hill HDR reservoir under a variety of scenarios.

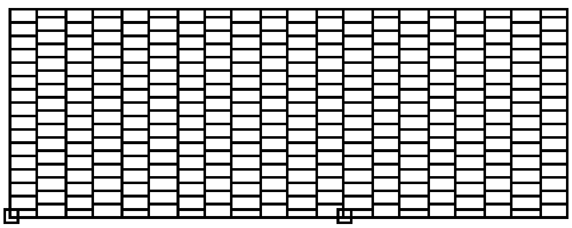


Figure 25. Mesh used to model the Fenton Hill fractured reservoir. Points indicated by small squares are the entrance to and exit from the reservoir, at each of which, boundary conditions are specified.

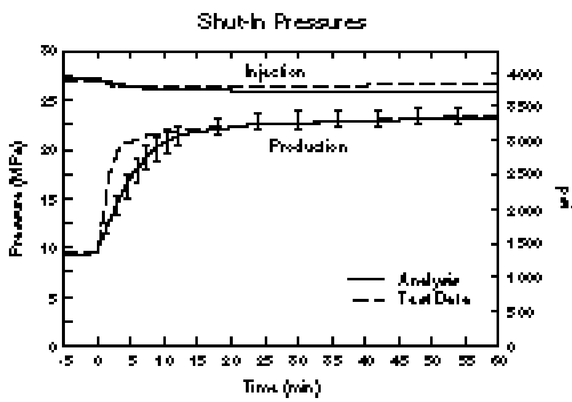


Figure 26. Actual and modeled wellhead pressures following simultaneous shut in of both Fenton Hill wells at time zero.

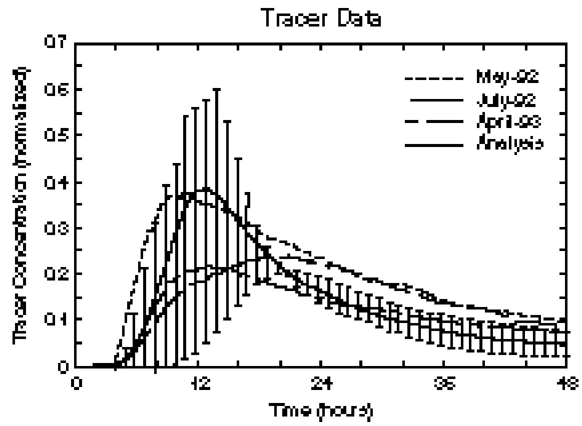


Figure 27. Actual and modeled tracer response at the Fenton Hill production well.

Results obtained with the model point to possible methods for improving reservoir performance. Both reservoir observations and calculations show that a significant fraction of the reservoir impedance occurs near the production well. Reducing this impedance has the potential for increasing production. In addition, it should be possible to increase the distances between wells, thus increasing the volume of hot rock accessed by the reservoir, without unduly increasing the system impedance.

Reservoir impedance can also be reduced by increasing reservoir pressure and further opening the fluid-carrying joints, however, there is a limit to the maximum injection pressure that can be applied without extending the reservoir. In the development of future HDR systems, proper spacing and location of production wells can provide effective pressure relief, allowing a higher injection pressure and thereby making it possible to increase production.

Technology Transfer

The Clearlake HDR Initiative: The city of Clearlake is situated on the shores of Clear Lake, the largest natural body of fresh water in the state of California. It also lies in the northern part of the Geysers-Clear Lake geothermal anomaly that is the source of the heat for The Geysers hydrothermal steam field. A number of exploratory wells have been drilled in the vicinity of Clearlake in an effort to discover hydrothermal resources, but none of them have produced fluid in commercial quantities. As a result of these explorations, however, a large amount of data regarding the geological characteristics of the region have been generated. The high terrestrial heat flows detected indicate that the Clear Lake region may lie atop one of the best HDR prospects in the United States.

A number of years ago, the city of Clearlake, California, became interested in the potential for developing its geothermal resources. In the late 1980s, Los Alamos provided a preliminary evaluation of the HDR resources in the Clearlake area. Under a contract administered by the city of Clearlake with funds appropriated by the California Energy Commission, work was begun in 1991 on a much larger, in-depth study of the potential for HDR development at Clearlake. The study was organized on a task basis and entailed the compilation and integration of available information about the geological and hydrological characteristics of the Clearlake area, as well as a small amount of field work. It came to fruition in 1993 with the completion of the initial drafts of the following reports:

- Task A, Thermometry: “Heat Flow and Hot Dry Rock Geothermal Resources of the Clearlake Region, Northern California,” 84 pp., by Kerry Burns

- Task B, Geological Structure: “Geological Structure and Paleotectonics of the Clearlake Region, Northern California,” 61 pp., by Kerry Burns

- Task C, Geohydrology: “Geochemistry of Thermal/Mineral Waters in the Clearlake Region, California, and Implications for Hot Dry Rock Geothermal Development,” 23 pp., by Fraser Goff, Andrew I. Adams, P. E. Trujillo, D. Counce, and John Mansfield

- Task D, Seismicity: “Neotectonics and Seismicity of the Clearlake Region, Northern California, 29 pp., by Kerry Burns

- Task E, Geothermal Regimes: “Geothermal Regimes of the Clearlake Region, Northern California,” 108 pp., by Kerry Burns

- Task F, Surface Water Hydrology: “Surface Water Supply for the Clearlake, California, Hot Dry Rock Geothermal Project,” 39 pp., by Alan R. Jager

The entire body of work is synopsized in a 39-page executive summary by Kerry Burns, the project leader, entitled "Geothermal Regimes Near the City of Clearlake." The task reports and the executive summary have been peer-reviewed and are undergoing final revisions as this is written. It is expected that they will be available to the public through the California Energy Commission before the end of 1994.

Direct Industrial Contacts: Transfer of HDR technology to industry was promoted through one-on-one visits with more than a dozen private firms during Fiscal Year 1993. Some of these meetings took place at Los Alamos and offered an opportunity for industry people to see the Fenton Hill HDR site, while others were held at the place of business of the industrial party or at incidental locations selected for mutual convenience. Multiple contacts were made with a number of firms and working relationships were established with several. Memoranda of Agreement to work jointly toward the implementation of HDR technology were signed with three organizations.

Perhaps the most specific outgrowth of technology transfer activities during this year was a bid by Geolectric Company, a small geothermal firm, to provide electricity to Portland General Electric (PGE) that would be derived in part from HDR resources. The bid was in response to a "Green" Request for Proposal (RFP) from PGE soliciting electric power produced by environmentally clean technologies. In a related development, PGE conducted a series of meetings during 1993 that led to the development of position papers outlining the prospects for the various alternative energy technologies to contribute to their power supply portfolio. The geothermal paper included a significant discussion of the status of HDR technology development and the potential for HDR to become a viable resource option for PGE.

Meetings, Workshops, and Conferences: Presentations discussing HDR were made at a number of regularly scheduled conferences such as the Geothermal Resources Council (GRC) Annual Meeting and the DOE Geothermal Technology Division Program Review. These presentations served to bring an audience representing a broad spectrum of the geothermal and energy industries up to date on developments in HDR technology and application. In addition, several meetings devoted specifically to HDR were convened during 1993.

In January 1993, a two-day workshop in Philadelphia attracted more than 100 attendees to discuss HDR issues. The first day of the workshop was sponsored by the Electric Power Research Institute (EPRI). It focused on the HDR potential for the US electric utility industry and addressed the basic aspects of HDR technology, the HDR resource base, economics of HDR-based electricity generation, and the infrastructure needed to facilitate HDR use.

A report on the EPRI workshop (EPRI Project RP1994-06) is available from Dr. Paul Kruger, organizer of the meeting, or Evan Hughes, EPRI Project Manager for Hydroelectric Generation and Renewable Fuels Programs. The second day of the workshop was organized by John Sass of the US Geological Survey. In response to directive in Section 2502 of the National Energy Policy Act of 1992, it addressed the potential of HDR geothermal energy in the eastern US. This part of the workshop discussed the definition of HDR from a geological point of view, the magnitude of the HDR resource, and its distribution east of the Rocky Mountains. A report on this part of the workshop is available from the US Geological Survey (USGS Open-file Report 93-377).

During the early part of the fiscal year, a special HDR briefing was held in conjunction with the GRC meeting in San Diego, California. Fifty representatives of industrial firms, government agencies and international HDR projects were updated on the results of recent flow testing at Fenton Hill and plans for working closely with American industry to further develop and implement HDR technology.

A few months later, the first formal meeting of the HDR Technology Commercialization Board (a successor industrial advisory group to the Program Development Council) took place on April 15, 1993, in Albuquerque, New Mexico. The prospective board members in attendance included representatives from utilities, geothermal companies, regulatory agencies, and universities. This latter meeting was convened just as the flow testing at Fenton Hill was being terminated because of a funding shortfall. Although the funding problem was not resolved at the meeting, it did provide the occasion for the suggestion by the DOE that a Notice of Program Interest be prepared to formally solicit industry interest in a joint HDR development project. As discussed below, such a document was subsequently prepared and published.

DOE Notice of Program Interest: In an effort to explore the possibility of developing a cost-shared project to implement HDR technology, a Notice of Program Interest was formulated during the summer of 1993. The Notice was published in September 1993 in the Commerce Business Daily and the Federal Register, and subsequently reprinted in the Geothermal Resources Council Bulletin. It solicited comments from private industry and nonfederal public agencies in regard to an industry-led project to develop a prototype facility to produce and market electric power or heat from the geothermal energy in HDR. By early in Fiscal Year 1994, 41 organizations had replied to the Notice. Respondents included geothermal developers, alternative energy companies, engineering firms, utilities, equipment manufacturers, universities, and state energy agencies. Most of those replying expressed a high level of interest in being a part of the proposed project and a number of them expressly discussed jointly funding the work.

Based on the level of interest expressed in response to this Notice, as well as on the highly positive flow test results discussed elsewhere in this report, the DOE decided to go forward with a formal solicitation seeking an industrial consortium to develop a plant to produce and market energy derived from an HDR resource. It is expected that the industry-led HDR project will build on the accumulated results of more than 20 years of work at Fenton Hill and elsewhere to bring about the first practical application of HDR technology.

HDR PROGRAM MANAGEMENT

Organization

As shown in Figure 28 the HDR Program continues to be field-managed jointly by the Los Alamos National Laboratory (LANL) and the DOE Albuquerque Operations Office (DOE/ALO) under the overall purview of the Geothermal Technology Division of the DOE (DOE/GTD). Gladys Hooper is the DOE/GTD Program Manager, Dan Sanchez is the DOE/ALO Field Manager, and David Duchane is the Los Alamos Program Manager. The Technology Commercialization Board is an industrial advisory group being set up to succeed the Program Development Council as a point of private sector input to the HDR Program. It will provide guidance on developing increased participation in HDR technology by private industry.

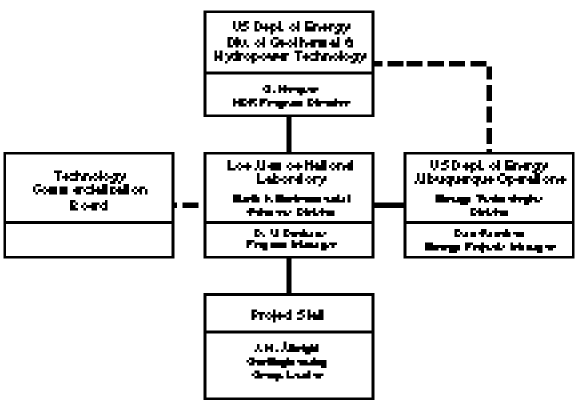


Figure 28. HDR Program management structure.

Frequent contact is maintained among the organizations in Los Alamos, Albuquerque, and Washington involved in managing the HDR Program. At Los Alamos, David Duchane became Program Manager for the HDR Program in February 1990. He works closely with the EES Division Office, the Energy Technologies Program office, and the EES-4 Group Leader in directing the Los Alamos effort. Los Alamos management entails both direct program management and management support and services.

Direct program management involves the responsibility for overseeing, controlling, representing, and communicating on behalf of the HDR Program in both the technical and administrative areas. Responsibilities in this area include the following activities:

- Providing day-to-day programmatic direction to functional personnel.
- Carrying out technical and fiscal planning including preparation of the Annual Operating Plan (AOP), plans for field experiments, and budgetary accounting analyses.
- Communicating program information both informally and by means of written reports and semiannual presentations to the DOE/GTD.
- Supporting requests from the DOE/GTD for programmatic information or other input.
- In concert with DOE/ALO, interfacing with and providing required reports to state and local government agencies and local offices of other federal agencies including the USGS, US Forest Service, EPA, BLM, New Mexico State Engineer's Office, and New Mexico State Bureau of Economic Geology.
- Assisting the Los Alamos Area Office of DOE in the processing and approval of major subcontracts and procurements and supporting that office in the settlement of any claims or labor disputes arising in connection with the HDR Program.
- Maintaining liaison with other HDR-related programs and relevant industrial organizations.
- Fostering the transfer of HDR technology to industry.
- Providing information and tours to governmental, industrial, and institutional visitors as appropriate.
- Conducting reviews of the HDR Program with the HDR Technology Commercialization Board.
- Coordinating the HDR Program with other LANL Programs.
- Representing the HDR Program to LANL upper management and other Laboratory organizations.

Management support and service functions include:

- LANL upper management attention to HDR Program matters, as required.

- Procurement, personnel, security, and legal services.

- Editorial and publication support.

- Fiscal and accounting support.

Interfaces

As described above, Los Alamos management interfaces with the DOE at several levels, as well as other federal agencies including the USGS, US Forest Service, Environmental Protection Agency, Bureau of Land Management; state government organizations such as the New Mexico State Engineer and New Mexico State Bureau of Economic Geology; and local governments. Frequent interfaces with business, industry, and the press arise out of technology transfer activities, which may take the form of visits, phone calls, written correspondence, etc. These activities also lead to interfaces with a variety of governmental entities not specifically mentioned above on an ad hoc basis, as well as a significant number of international contacts. The relationships developed with the city of Clearlake, California, and the California Energy Commission are particularly noteworthy in this regard.

Attendance at professional meetings, presentation of papers and talks, program reviews, and meetings of advisory groups such as the Technology Commercialization Board entail further interactions with wide segments of the business, technical, governmental, and professional communities. Finally, as described above, intralaboratory interfaces are an important component of the HDR effort. The following is a brief summary of HDR Program interfaces during Fiscal Year 1993. Details of these interfaces are found in the Appendix.

INTERNATIONAL

Japan	25 visitors
France	1 visitor
Italy	1 visitor
Sweden	1 visitor
Ukraine	1 visitor
United Nations	3 visitors

INDUSTRIAL

AWS Scientific
RE/SPEC Inc.
Texaco
Constellation Energy, Inc.
Howell Corporation
Lincoln Electric Systems
S.A. Holdage & Associates
Motorola
Geothermal Systems Corporation
Weiss Associates
Metger, Hollis, Gordon, & Mortimer
Geolectric Power Co.

GOVERNMENTAL

Office of US Representative: Bill Richardson
Office of US Representative: Dan Hamberg
California Energy Commission
City of Clearlake, California
California Division of Oil and Gas
Colorado Center for Environmental Management
Arizona Department of Commerce
Sandia National Laboratories
Brookhaven National Laboratory
U.S. Department of Defense
U.S. Government Accounting Office
National Renewable Energy Laboratory
U.S. Bureau of Mines
U.S. Forest Service
U.S. Geological Survey

NONPROFIT ORGANIZATIONS AND PROFESSIONAL SOCIETIES

Sierra Club
Electric Power Research Institute

ACADEMIC

Gustavus Adolphus College
Colorado College
Stanford University
Armand Hammer United World College of the American West
University of Nebraska, Lincoln
Kansas State University
University of Arizona
University of Utah
Arroyo Grande, California, High School
Massachusetts Institute of Technology
University of Texas
Sandia Preparatory School
New Mexico Institute of Mining & Technology
University of New Mexico Center for the Study of Japanese Industry
University of Texas at Austin, US-Japan Center for Technology Management

MEDIA

Science Magazine
Baltimore Sun
Earth Magazine
Albuquerque Journal
Energy Report
Los Alamos Monitor
San Francisco Chronicle
Geothermal Resources Council Bulletin
Fortune Magazine
Independent Power Report
Santa Fe New Mexican
Power Line Magazine
Lake County Record-Bee
Geothermal Hot Line
Lincoln Journal-Star
Independent Power Report
Fortune
BRIEF Magazine
Popular Science Magazines
Christian Science Monitor
KOVR-TV
ABC-TV
KNME-TV
ENVIRO VIDEO
KXBX-Radio
WAEC-Radio
CBS-Radio

MEETINGS

Members of the HDR staff participated in 13 professional and technical meetings.

BUDGET

As illustrated in Table 6, the severe budget restrictions in recent years have impeded progress in bringing HDR technology to fruition. Limited budgets during the late 1980s and early 1990s led to delays in completion of the surface plant at Fenton Hill. A one-year budget increase in Fiscal Year 1992 coincided with the start of long-term flow testing. Unfortunately, a significantly reduced budget in Fiscal Year 1993 forced premature termination of the flow testing program. The results presented in this report, while encouraging, are thus less than they might have been given an adequate budget to continue testing through the end of 1993.

The budget for Fiscal Year 1994 is too small to provide for any flow testing at all. The Fenton Hill site will therefore be maintained on standby status while plans for an industry-led program to construct and operate a facility which can produce and market energy from HDR resources are developed. Limited data analysis, modeling, and low-cost, static testing will be performed during 1994 in order to provide important information for potential participants in the industry-led effort.

As this report is being written, the budget outlook for Fiscal Year 1995 is somewhat more promising. The USDOE has requested an appropriation of $4.1 million to maintain the Fenton Hill HDR facility and initiate an industry-led, cost-shared project to produce and market energy derived from an HDR resource. Current planning envisions the issuance of a solicitation of partners for the industry-led project in early Fiscal Year 1995 and the selection of an industrial consortium to carry out the project later in the year.

In preliminary announcements, the USDOE has stated that it is prepared to participate in a joint industry/government program to commercialize HDR at funding levels totaling as high as $30 million. If the industry-led project is to lead to a practical HDR plant on line before the end of the decade, the federal budget appropriations for the technology during the next few years will have to be significantly larger than they have been in recent years. The payoff for this temporarily increased outlay of funds will be the entry of HDR into the energy market as a fully competitive player capable of providing clean energy at competitive prices, the development of export markets for American products and expertise, and good jobs for the domestic economy.

TABLE 6
HDR Program Budget History ($K)

Task/Project	Fiscal Year 1990	1991	1992	1993	1994*
Fenton Hill Site Operations	2471	2483	3193	1973	750
Phase II Energy Extraction System	588	1610	2210	1113	100
Phase II Ancillary Activities	284	320	400	280	260
Test Site Support	599	553	583	580	480
Scientific & Engineering Support	829	817	677	495	500
Engineering Development Activities	729	725	571	330	210
Technology Applications	100	92	106	165	300
Reserve and Miscellaneous	000	000	000	000	000
Total	3300	3300	3870	2468	1250

* Allocated as of 7/1/94

FUTURE PLANS

The results of the flow testing conducted at Fenton Hill during 1992-1993, as described in this report, have set the stage for the development of a practical HDR facility that will operate on a sustained basis. In late 1993, the USDOE published a "Notice of Program Interest" soliciting private sector input in regard to a joint government/industry project to construct and operate just such a plant. Forty-one replies were received from a variety of organizations. The high level of interest expressed by a number of the respondents has promoted the DOE to propose an increase in funding for HDR in Fiscal Year 1995 to a level of $4.1 million, after many years of shrinking budgets.

A solicitation for an industry-led HDR project to produce and market energy from HDR resources will be issued early in Fiscal Year 1995. It will be directed toward the development of a precommercial HDR energy facility to be designed and operated as a production plant. The government commitment will be limited to a total of $30 million over a multiyear period. A facility with a generating capacity of 1-25 MW electric (or 10-200 MW thermal) is envisioned, small enough to keep the total capital commitment within reasonable bounds but large enough to benefit from the economies of scale.

With government participation to help reduce the capital liability, and with engineering design aimed at significantly greater excess energy generation than can be achieved with the current plant configuration at Fenton Hill, it may be possible to operate a precommercial HDR power plant with a very favorable cost structure. Indications are that there is substantial private sector interest in modification and expansion of the Fenton Hill HDR facility to make it commercially viable, as well as in the development of HDR at entirely new locations.

Evaluation of industry responses to the solicitation should be completed by mid-1995. It is anticipated that preliminary site and permitting work will begin in 1995. It should then be possible to carry out drilling and reservoir development in 1996, conduct flow testing and construct a surface plant in 1997, and bring the jointly financed plant on-line in 1998.

The joint industry/government venture will provide a means for documenting the capital costs involved in developing HDR resources for power production. If constructed at a site geographically and geologically different from Fenton Hill, the facility will also help demonstrate the practicality of utilizing HDR resources from a variety of geological and geographical settings. Perhaps, most important, the revenue generated from plant operations will provide the financial incentive to operate the facility for several years or even decades, thus building the kind of track record required to convince even the harshest skeptics of the value of HDR technology.

Continued operation of the plant on an economically competitive basis will lead to the development of additional HDR facilities. Once energy production fro HDR has been successfully demonstrated at a number of high-grade resource locations, the economic and social benefits of other applications of HDR, such as production of thermal energy for direct use in low-grade resource locations and water purification in conjunction with energy production, will become increasingly apparent. Concurrently, improvements in the technical understanding of HDR reservoirs and in the design of HDR surface plants will increase the competitive position of the technology. As HDR technology matures in the 21st century, it will command a significant share of the worldwide energy market.